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Dehe et al.

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(54) **ELECTROSTATIC LOUDSPEAKER WITH MEMBRANE PERFORMING OUT-OF-PLANE DISPLACEMENT**

(75) Inventors: **Alfons Dehe**, Reutlingen (DE); **Mohsin Nawaz**, Unterhaching (DE); **Christoph Glacer**, Munich (DE)

(73) Assignee: **Infineon Technologies AG**, Neubiberg (DE)

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H04R 9/06	(2006.01)
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H04R 19/01	(2006.01)
H04R 7/04	(2006.01)

(52) **U.S. Cl.**

CPC ***H04R 19/02*** (2013.01); ***H04R 19/013*** (2013.01); *H04R 7/04* (2013.01)

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CPC H04R 19/04; H04R 3/00; H04R 19/016; H04R 19/02; H04R 19/013; H04R 19/005; H04R 19/01; H04R 19/00; H04R 9/025; H04R 9/06

USPC 381/191, 398, 174, 113, 116

See application file for complete search history.

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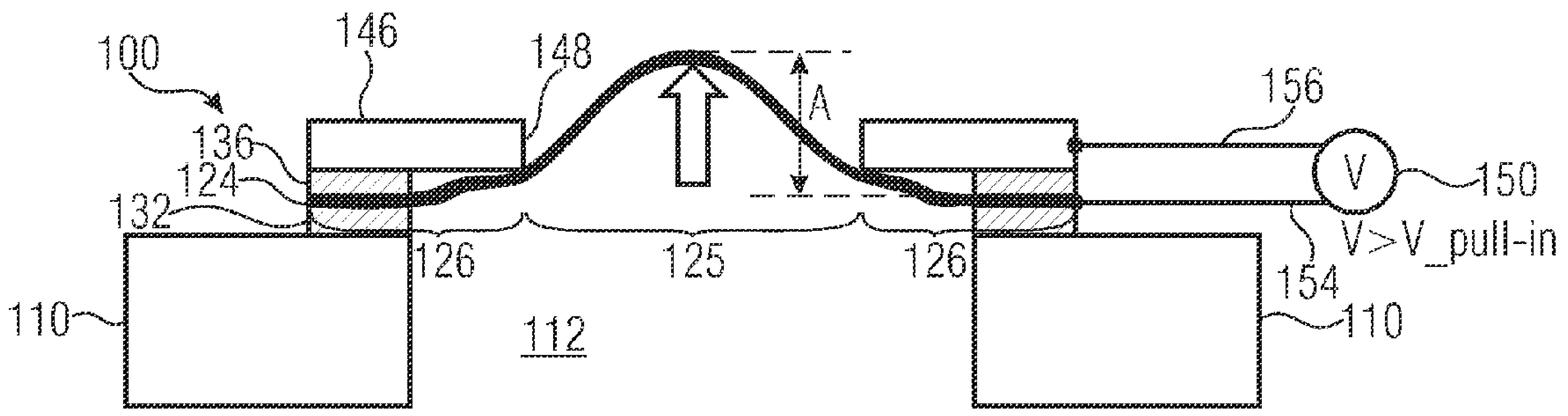
Primary Examiner — Matthew Eason
Assistant Examiner — Sean H Nguyen
(74) *Attorney, Agent, or Firm* — Banner & Witcoff, Ltd.

(57) **ABSTRACT**

An electrostatic loudspeaker comprises a membrane structure and an electrode structure. The membrane structure comprises a central membrane portion and a circumferential membrane portion. The electrode structure is configured to electrostatically interact with the membrane structure for causing a movement of the membrane structure along an axis of movement. The electrode structure comprises a circumferential electrode portion and an opening, the circumferential electrode portion being substantially aligned to the circumferential membrane portion and the opening being substantially aligned to the central membrane portion with respect to a direction parallel to the axis of movement. In an end position of the movement of the membrane structure, the central membrane portion is configured to extend at least partially through the opening. A method for operating an electrostatic loudspeaker and a method for manufacturing an electrostatic loudspeaker are also described.

25 Claims, 12 Drawing Sheets



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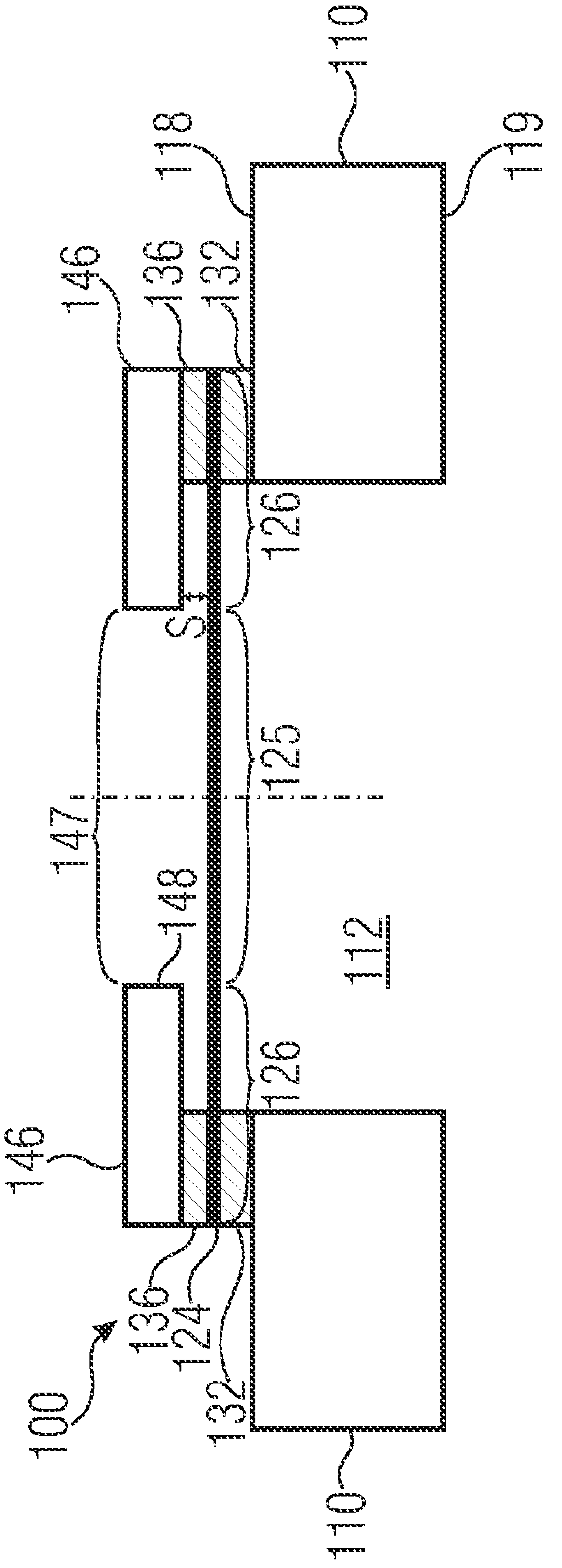

100
110
132
124
136
146
126
148
147
125
112
S1
126
132
136
146
118
110
119

FIG 1A

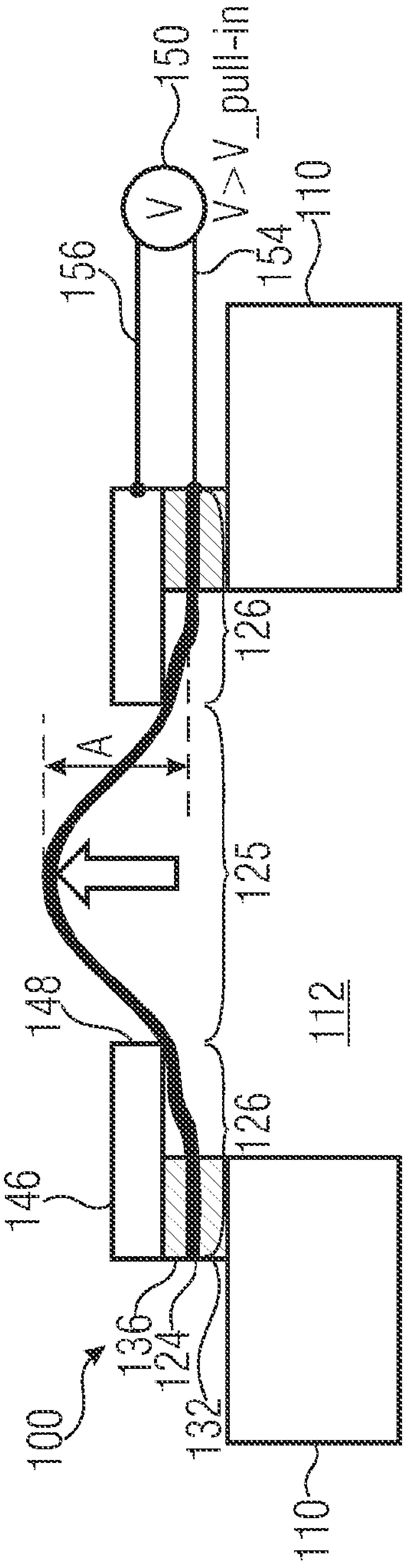

100
110
132
124
136
146
126
148
125
112
A
126
156
154
110
V
150
V>V_pull-in

FIG 1B

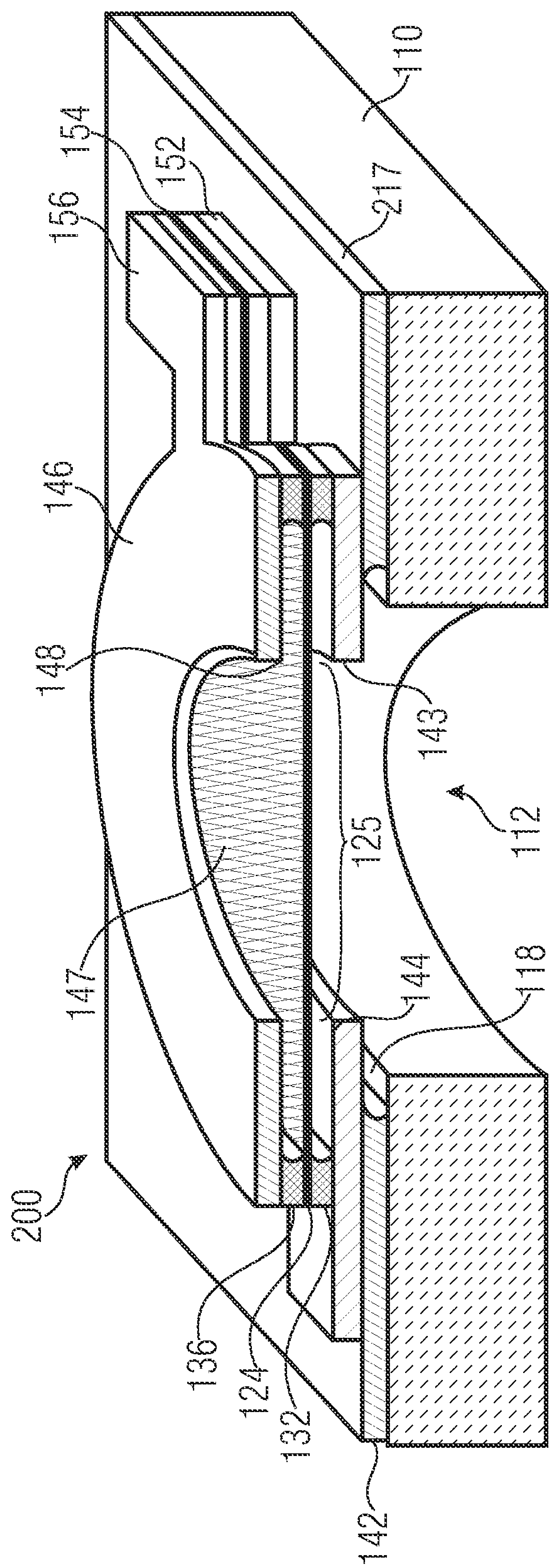

110
154
152
156
217
146
148
143
125
112
147
144
118
200
136
124
132
142

FIG 2A

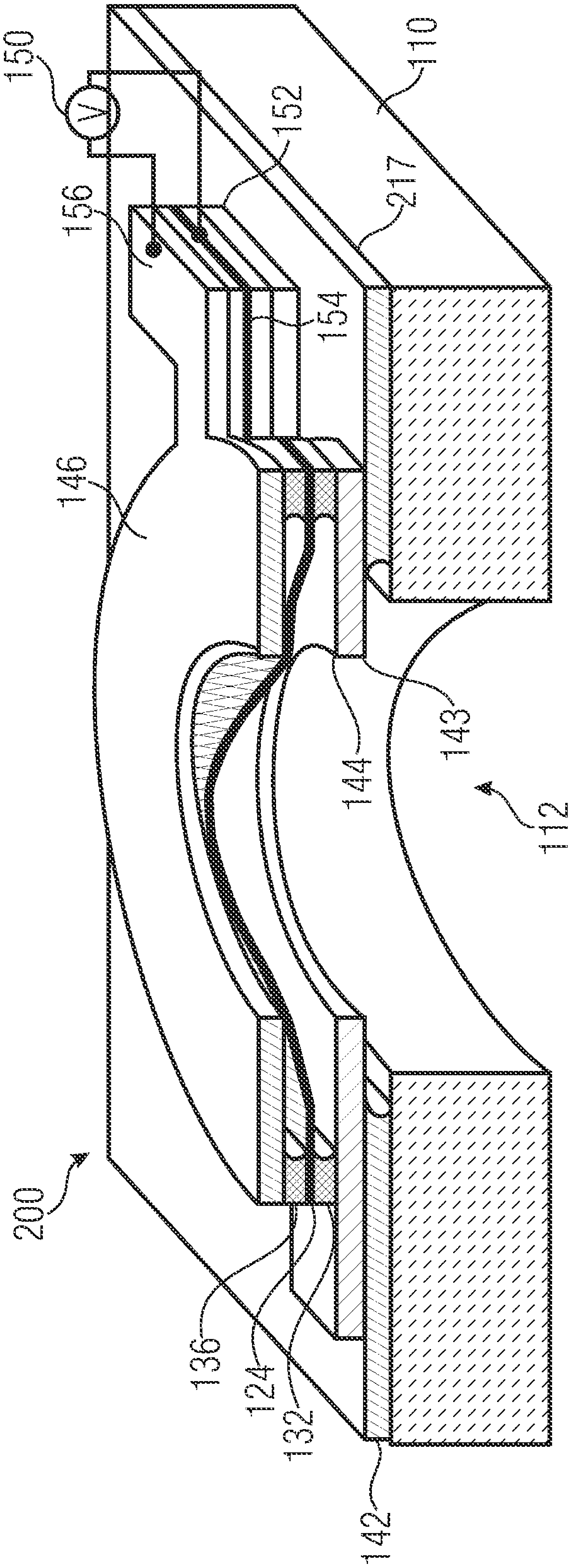


FIG 2B

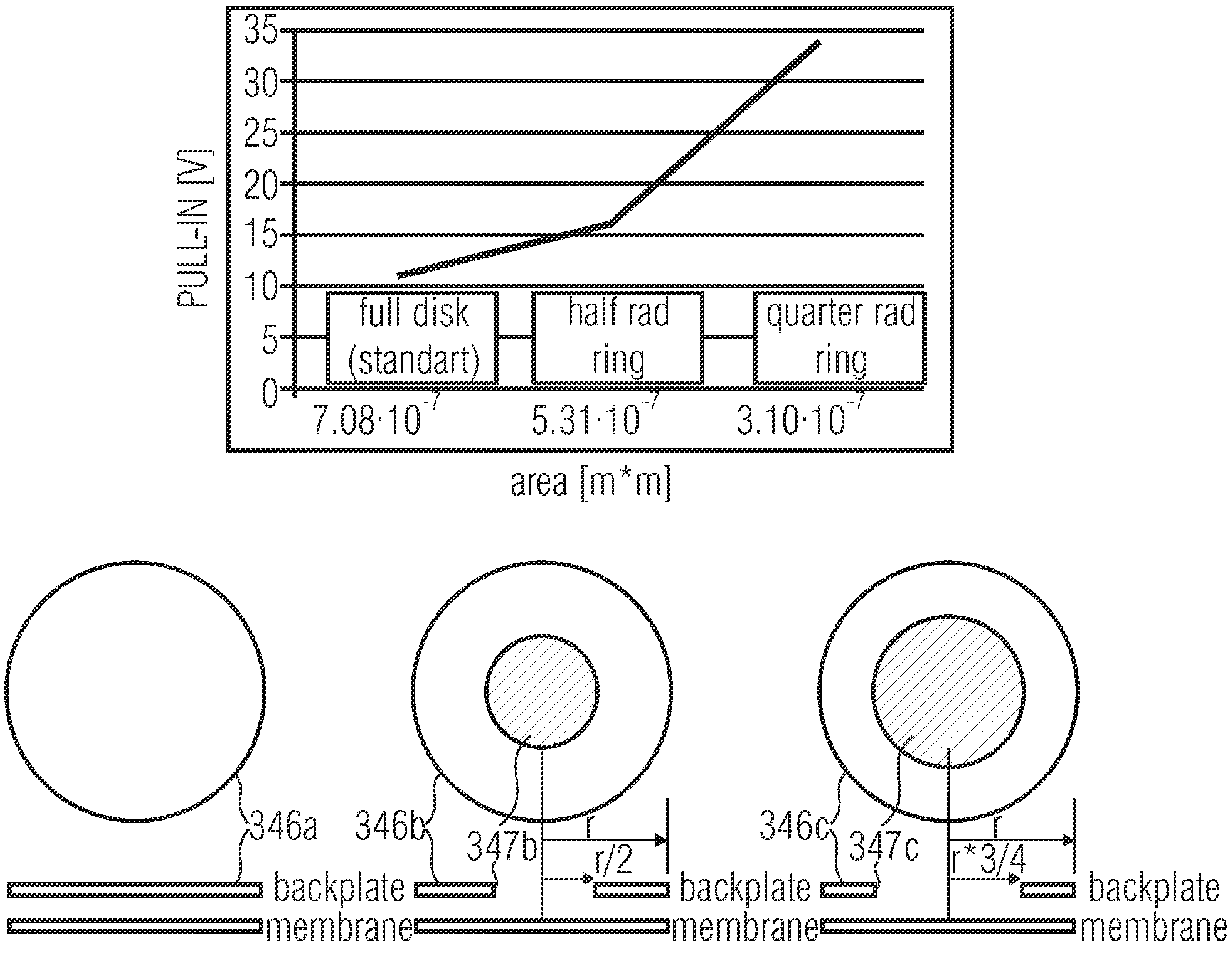

PULL-IN [V]
35
30
25
20
15
10
5
0
full disk (standart)
half rad ring
quarter rad ring
7.08·10^{-7}
5.31·10^{-7}
3.10·10^{-7}
area [m*m]
346a
backplate
membrane
346b
347b
r
r/2
backplate
membrane
346c
347c
r
r*3/4
backplate
membrane

FIG 3

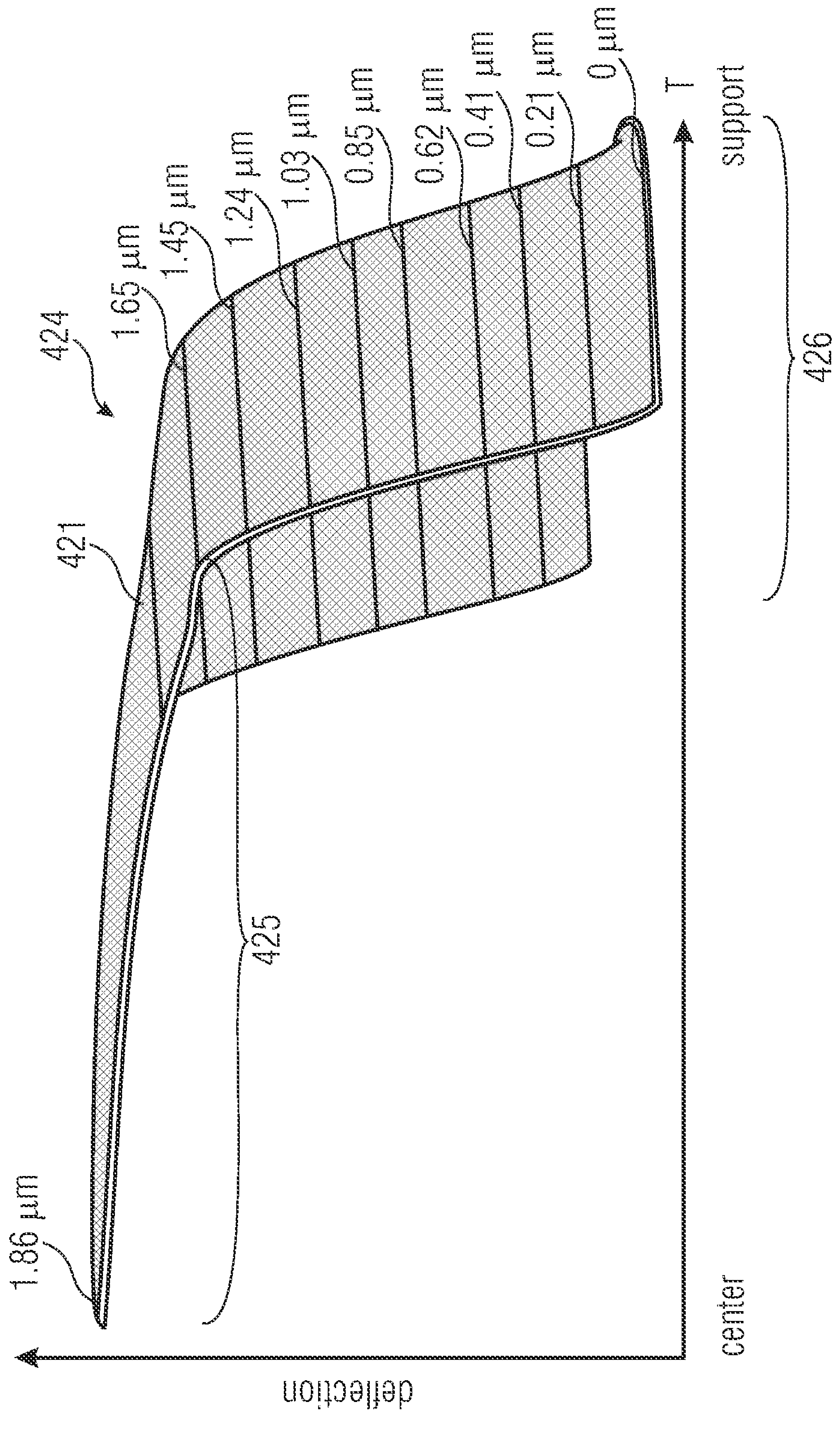

424
1.65 µm
1.45 µm
1.24 µm
1.03 µm
0.85 µm
0.62 µm
0.41 µm
0.21 µm
0 µm
T
support
426
421
425
1.86 µm
center
deflection

FIG 4

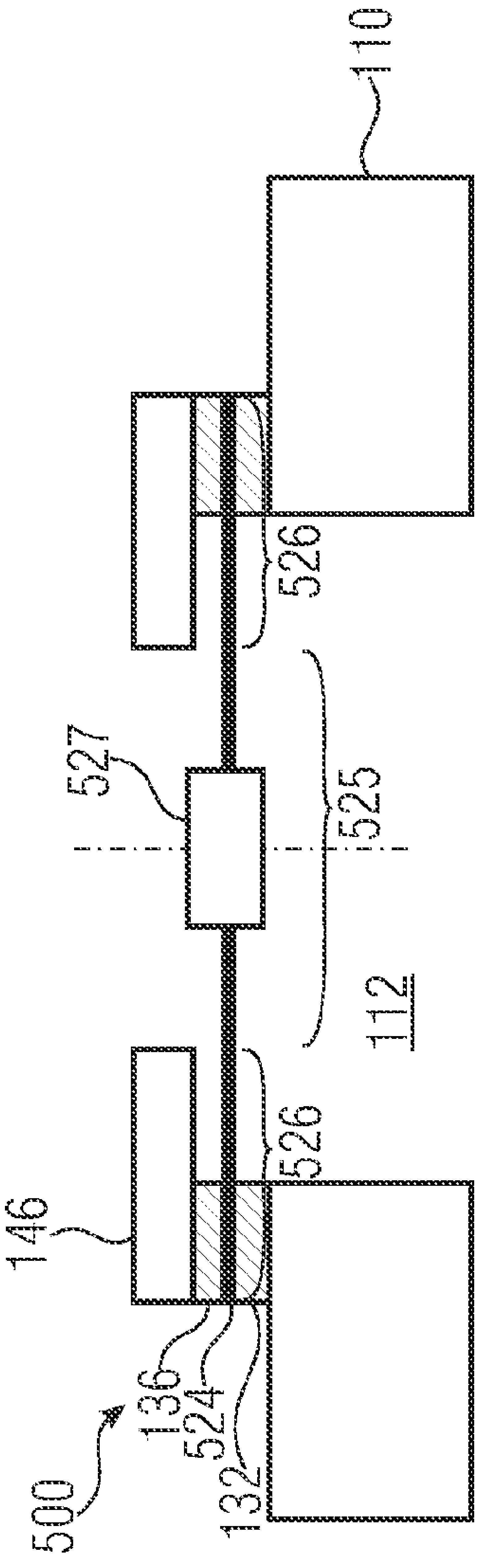

500
136
524
132
146
526
112
525
527
526
110

FIG 5A

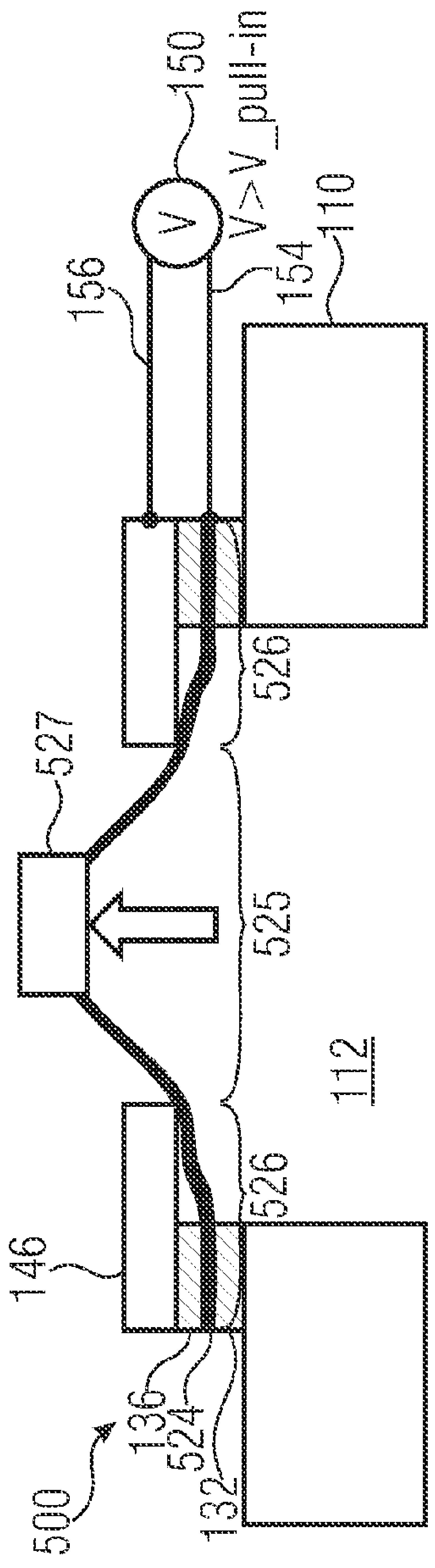

500
136
524
132
146
526
112
525
527
526
110
154
156
V
150
V> V_pull-in

FIG 5B

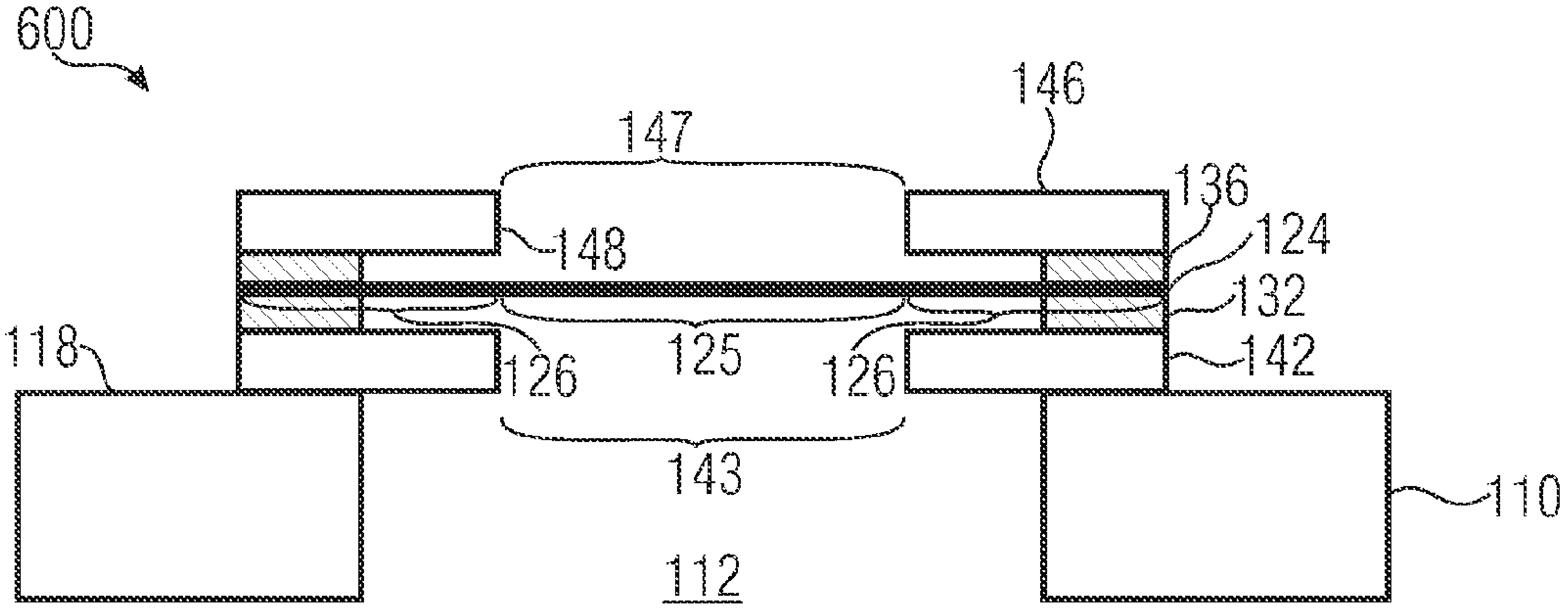

600
147
146
136
124
148
132
118
142
126
125
126
143
110
112

FIG 6

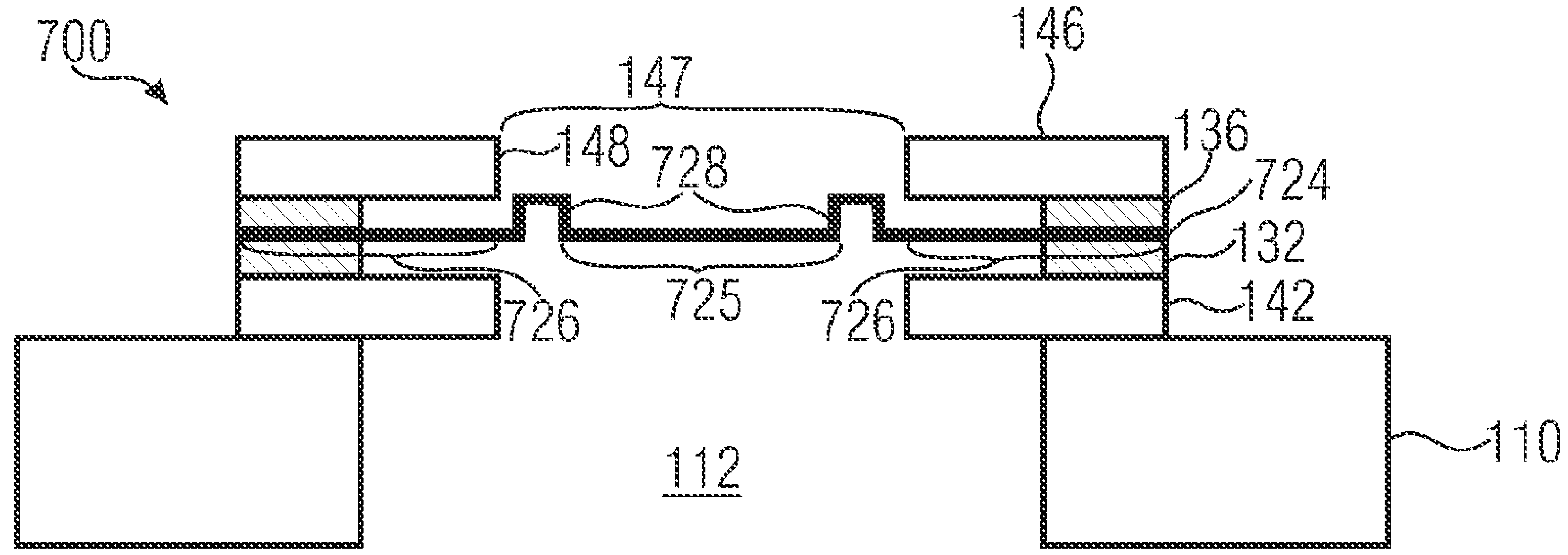

700
146
147
136
148
728
724
132
142
726
725
726
110
112

FIG 7

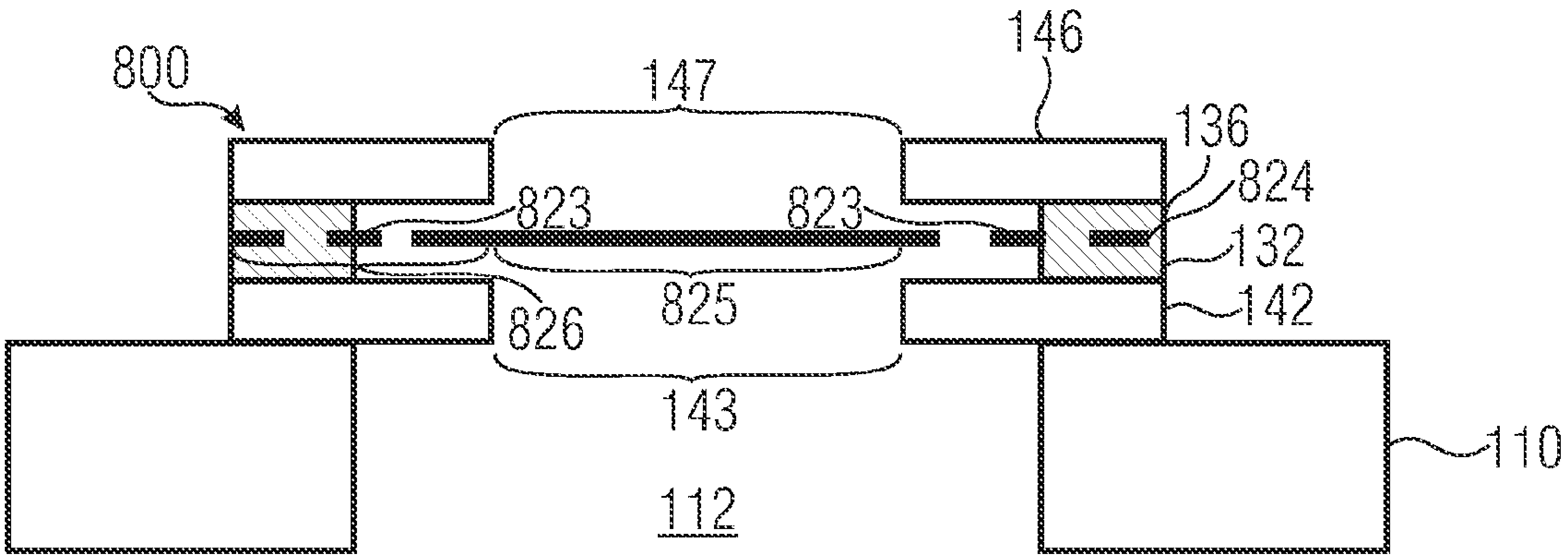

800
147
146
136
824
823
823
132
142
826
825
143
110
112

FIG 8A

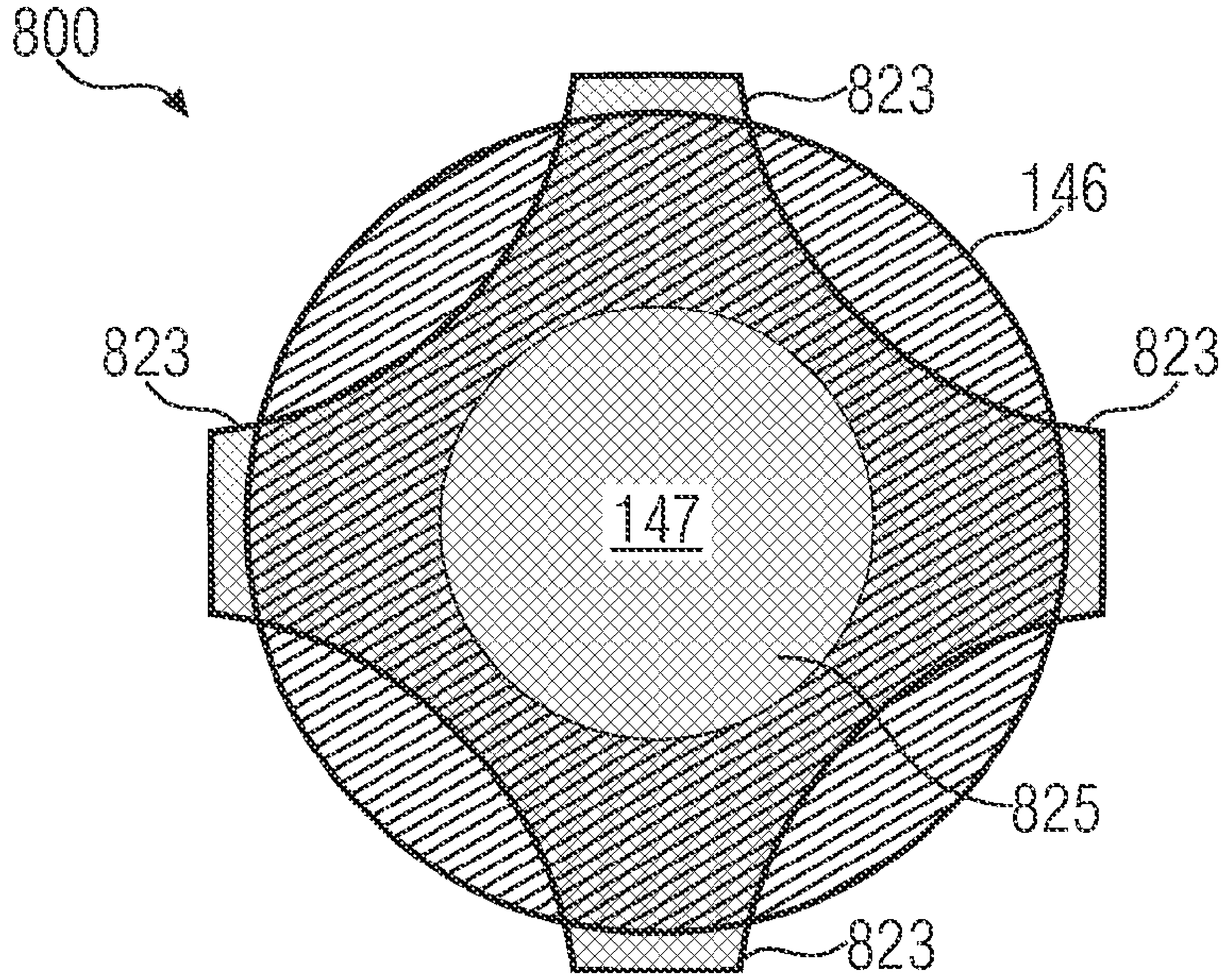

800
823
146
823
823
147
825
823

FIG 8B

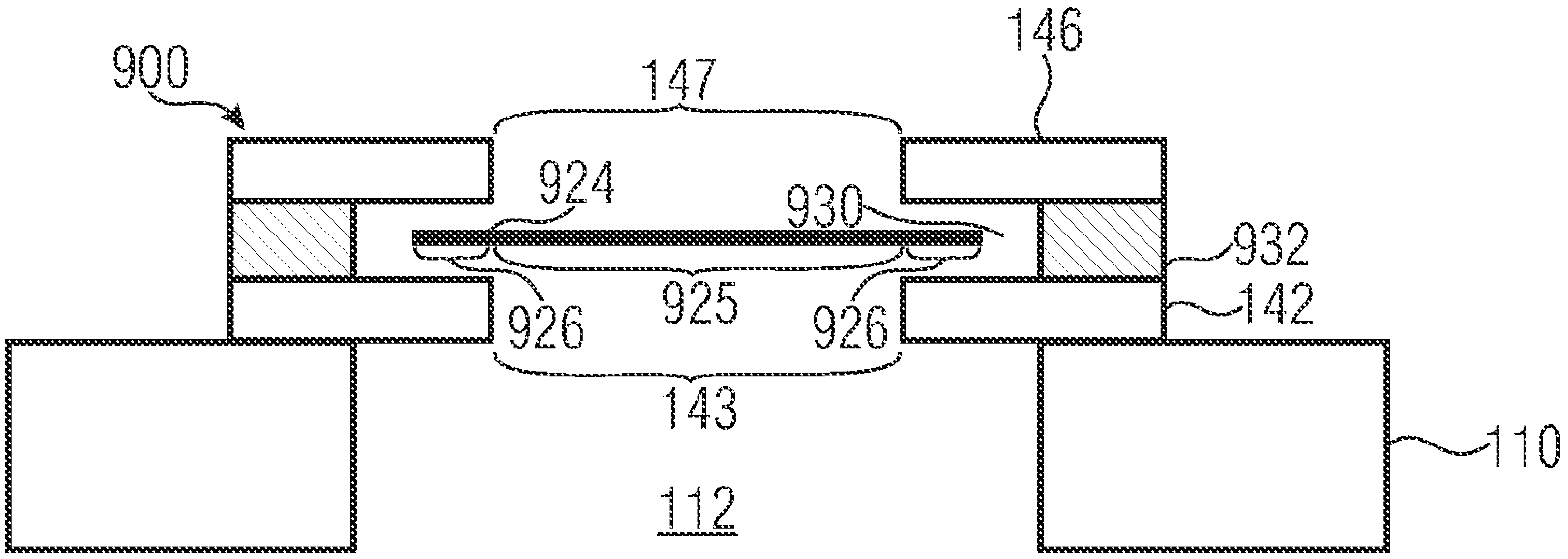

900
147
146
924
930
932
142
926
925
926
143
110
112

FIG 9A

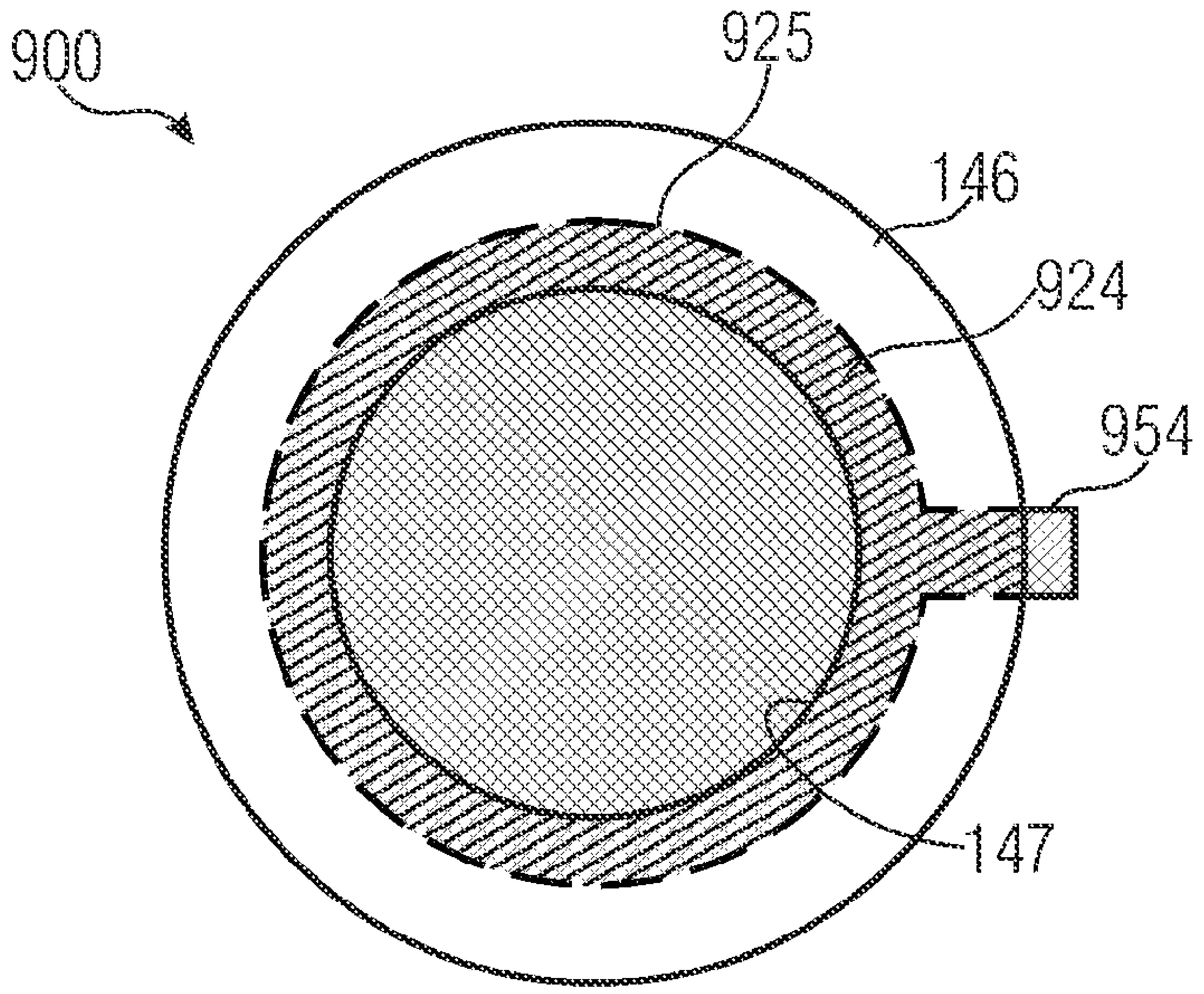

900
925
146
924
954
147

FIG 9B

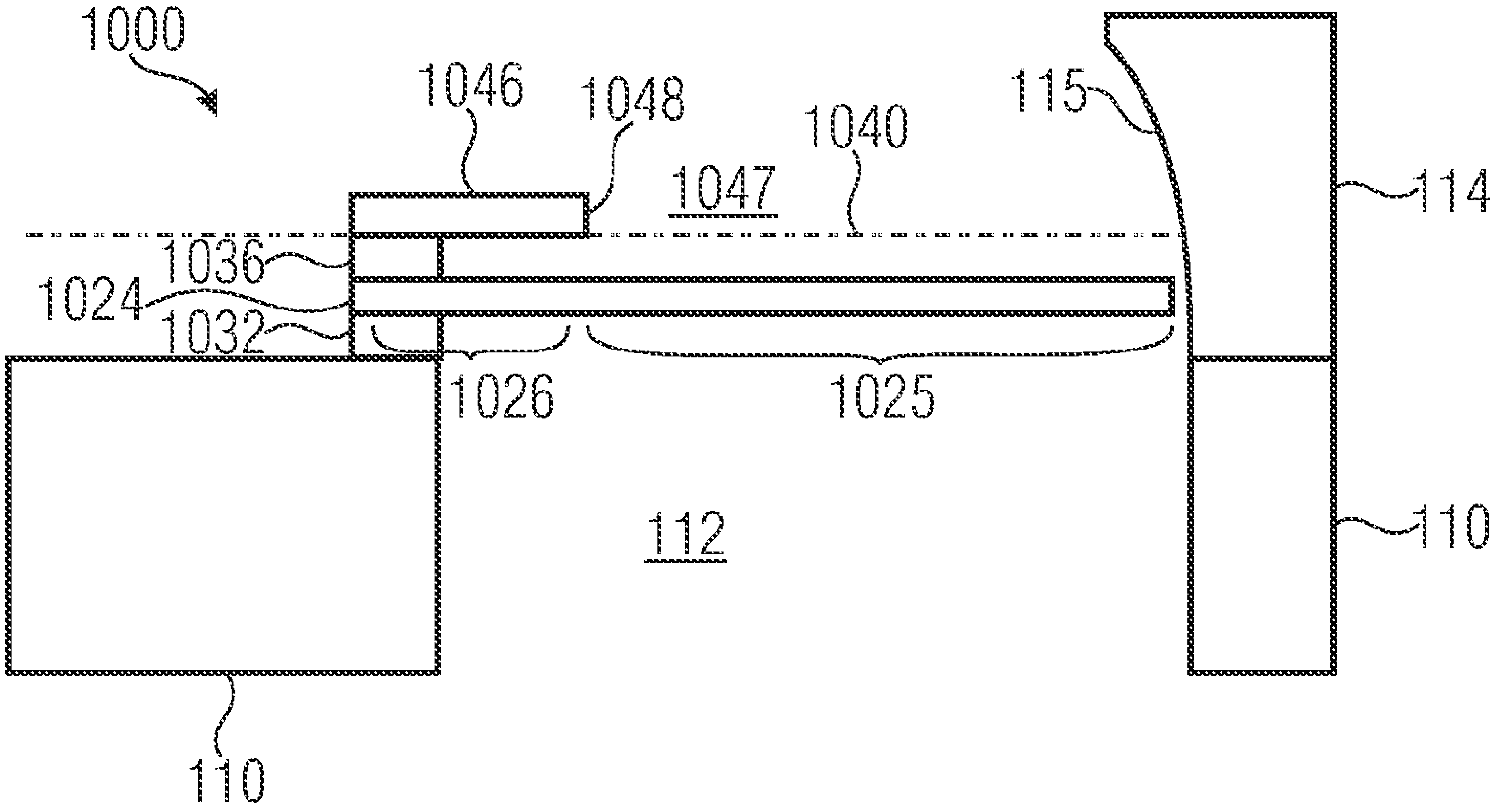


FIG 10A

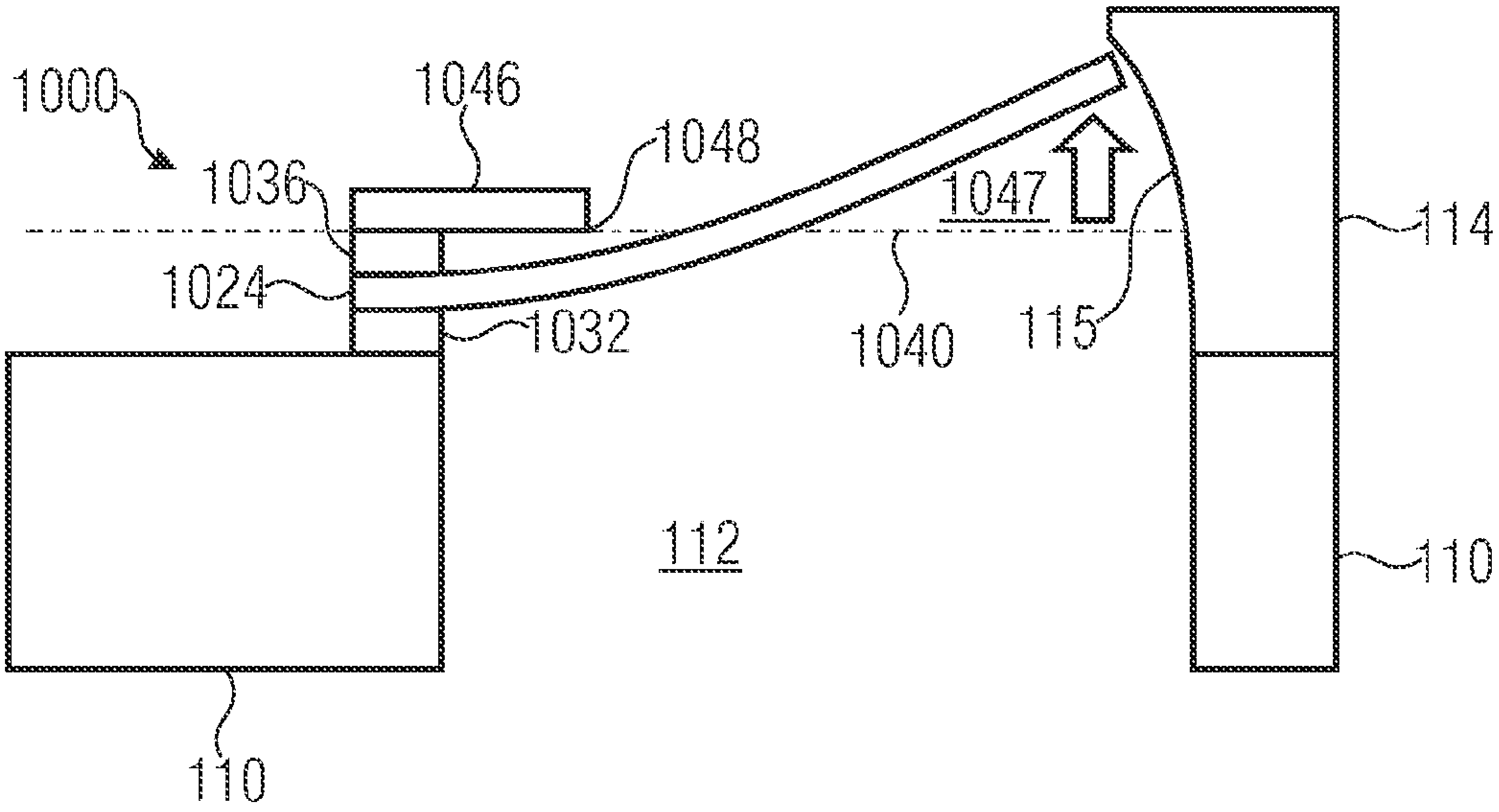
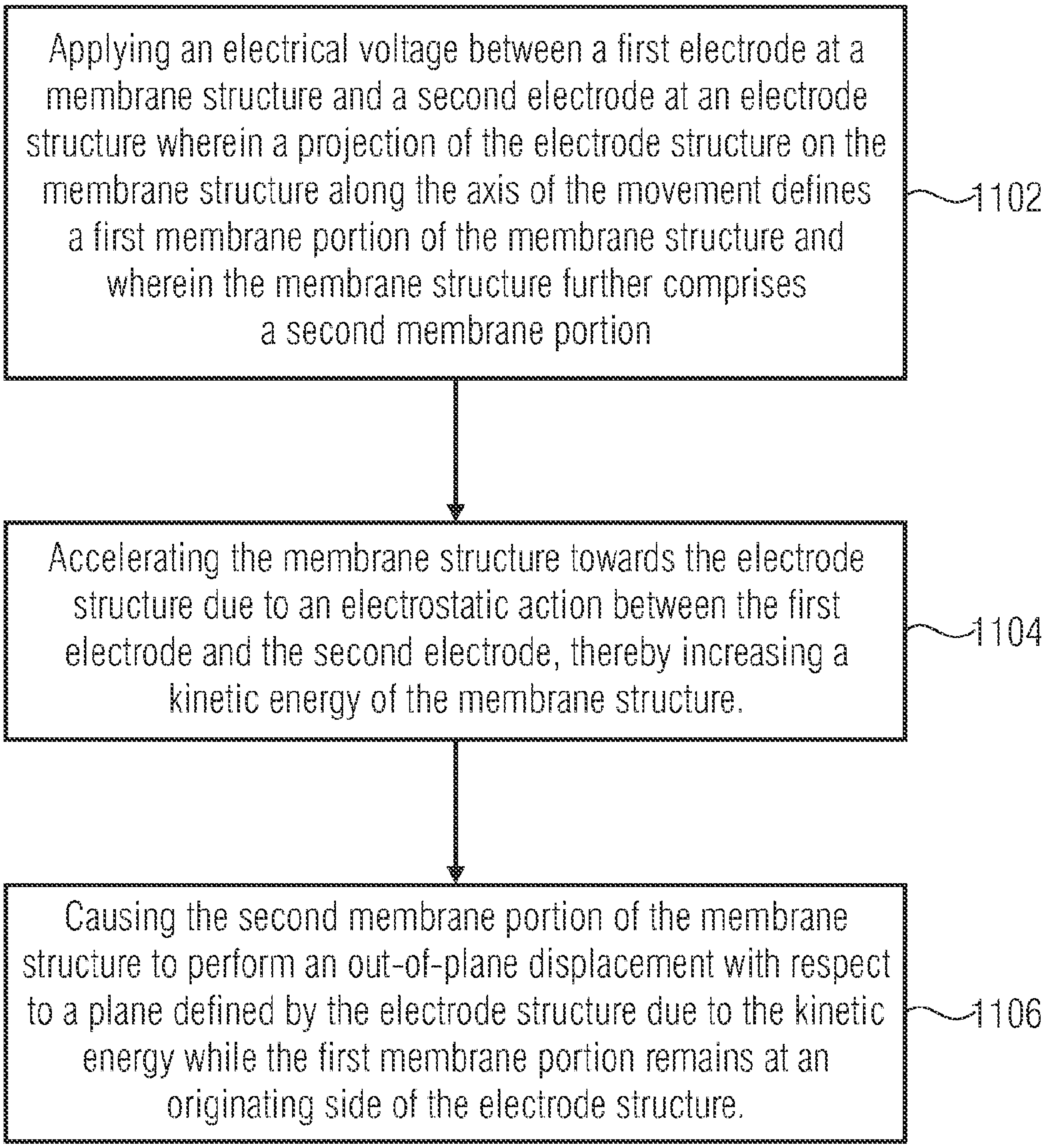


FIG 10B



Applying an electrical voltage between a first electrode at a membrane structure and a second electrode at an electrode structure wherein a projection of the electrode structure on the membrane structure along the axis of the movement defines a first membrane portion of the membrane structure and wherein the membrane structure further comprises a second membrane portion

Accelerating the membrane structure towards the electrode structure due to an electrostatic action between the first electrode and the second electrode, thereby increasing a kinetic energy of the membrane structure.

Causing the second membrane portion of the membrane structure to perform an out-of-plane displacement with respect to a plane defined by the electrode structure due to the kinetic energy while the first membrane portion remains at an originating side of the electrode structure.

FIG 11

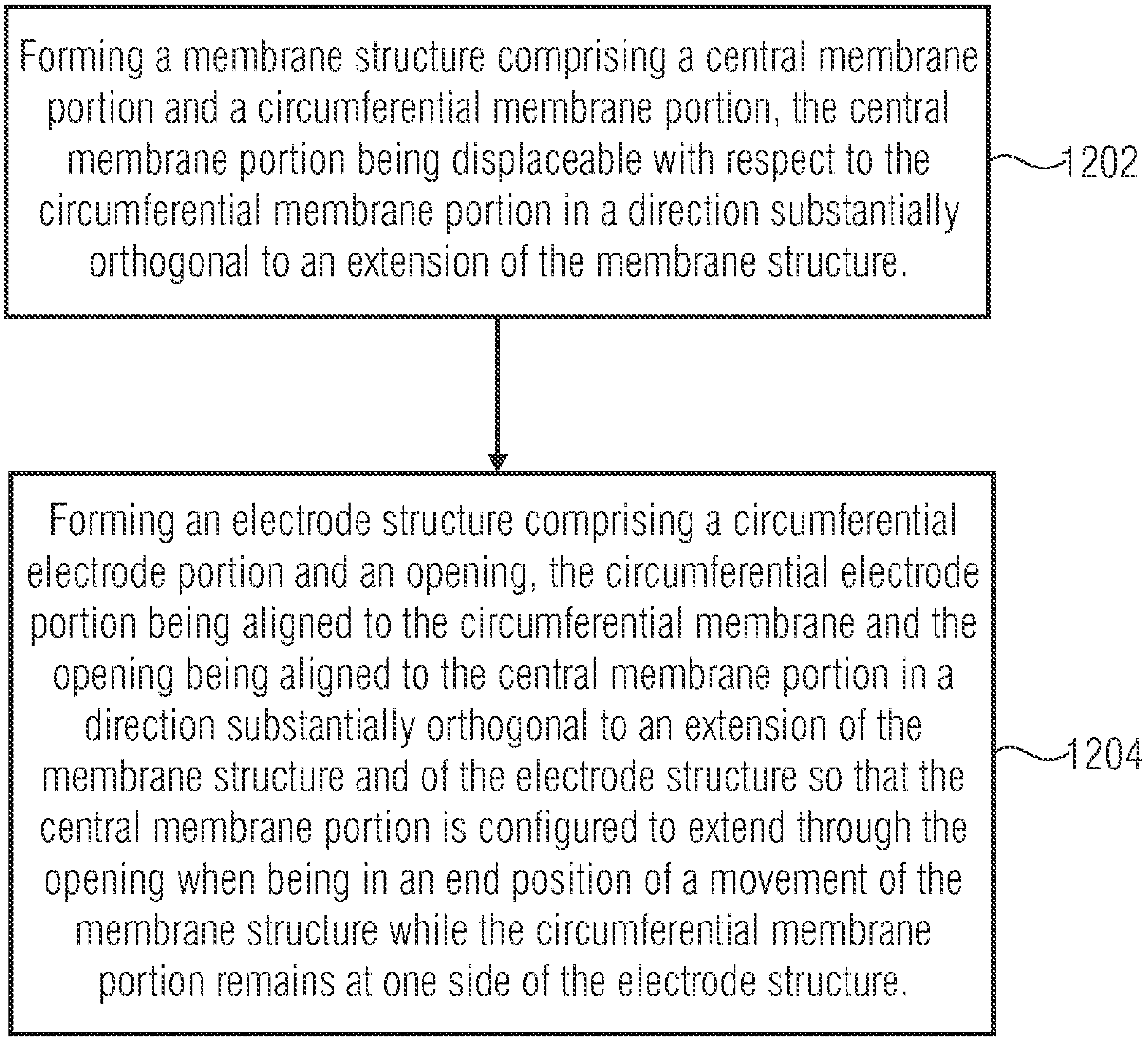

Forming a membrane structure comprising a central membrane portion and a circumferential membrane portion, the central membrane portion being displaceable with respect to the circumferential membrane portion in a direction substantially orthogonal to an extension of the membrane structure.
1202
Forming an electrode structure comprising a circumferential electrode portion and an opening, the circumferential electrode portion being aligned to the circumferential membrane and the opening being aligned to the central membrane portion in a direction substantially orthogonal to an extension of the membrane structure and of the electrode structure so that the central membrane portion is configured to extend through the opening when being in an end position of a movement of the membrane structure while the circumferential membrane portion remains at one side of the electrode structure.
1204

FIG 12

ELECTROSTATIC LOUDSPEAKER WITH MEMBRANE PERFORMING OUT-OF-PLANE DISPLACEMENT

TECHNICAL FIELD

Embodiments of the present invention relate to an electrostatic loudspeaker. Some embodiments of the present invention relate to a method for operating an electrostatic loudspeaker. Some embodiments of the present invention relate to a method for manufacturing an electrostatic loudspeaker. In particular, the electrostatic loudspeaker may be a micro electrical mechanical system (MEMS) and the method for manufacturing the electrostatic loudspeaker may employ micro electrical mechanical system fabrication technology, more particularly planar micro electrical mechanical technology.

BACKGROUND

An electrostatic loudspeaker uses a loudspeaker design in which sound is generated by the force exerted on a membrane suspended in an electrostatic field. Macroscopic electrostatic loudspeakers typically use a thin flat diaphragm usually consisting of a plastic sheet coated with a conductive material such as graphite sandwiched between two electrically conductive grids, with a small air gap between the diaphragm and the grids. The diaphragm in an electrostatic loudspeaker is typically driven uniformly over its entire surface as the electrostatic force acting on the diaphragm is created by one or two stators (electrodes) which have approximately the same area and are arranged substantially parallel to the diaphragm. For this reason, there is no need for the diaphragm to be particularly rigid. This fact is exploited in some designs of electrostatic loudspeakers where the diaphragm is made as light as possible. Moreover, electrostatic loudspeakers may be operated in a pull-pull mode which typically reduces distortions. As a result, an electrostatic transducer can operate over an exceptionally wide frequency range without having to cross over to another driver. Another attribute of most electrostatic speakers is their naturally dipolar radiation pattern. A true dipole transducer radiates with equal intensity from the front and back of its diaphragm, but the outputs are in opposite phase. In combination with the relatively large size of a typical electrostatic panel, output at the sides tends to be very low relative to that of a conventional loudspeaker, which in turn minimizes side-wall reflections that tend to muddle sonic detail and stereo imaging.

Electrostatic loudspeakers may be designed as micro electrical mechanical systems (MEMS). MEMS are potentially small scaled—of the order of tens of micrometers—and their fabrication is compatible with semiconductor-like processes (e.g., CMOS (Complementary Metal Oxide Semiconductor). This leads to potentially large volume manufacture.

SUMMARY

Embodiments of the present invention provide an electrostatic loudspeaker comprising a membrane structure and an electrode structure. The membrane structure comprises a central membrane portion and a circumferential membrane portion. The electrode structure is configured to electrostatically interact with the membrane structure for causing a movement of the membrane structure along an axis of movement. The electrode structure comprises a circumferential electrode portion and an opening. The circumferential electrode portion is substantially aligned to the circumferential membrane portion and the opening is substantially aligned to the central membrane portion with respect to a direction parallel to the axis of movement. The central membrane portion is configured to extend at least partially through the opening when being in an end position of the movement of the membrane structure.

Further embodiments of the present invention provide an electrostatic loudspeaker comprising a membrane structure and an electrode structure. The membrane structure is configured for displacement along an axis of movement. The electrode structure is configured to electrostatically interact with the membrane structure for causing the displacement. A projection of the electrode structure on the membrane structure along the axis of the movement defines a first portion of the membrane structure. The membrane structure further comprises a second portion. The membrane structure is configured so that the second portion deflects, due to a kinetic energy caused by the movement, at an edge of the electrode structure during phase of the movement of the membrane structure. The second portion is configured to perform an out-of-plane displacement with respect to a plane defined by the electrode structure.

Further embodiments of the present invention provide a method for operating an electrostatic loudspeaker. The method comprises applying an electrical voltage between a first electrode at a membrane structure and a second electrode at an electrode structure. A projection of the electrode structure on the membrane structure along an axis of movement of the membrane structure defines a first membrane portion of the membrane structure. The membrane structure further comprises a second membrane portion. The method further comprises accelerating the membrane structure towards the electrode structure due to an electrostatic action between the first electrode and the second electrode, thereby increasing a kinetic energy of the membrane structure. The method also comprises causing the second membrane portion of the membrane structure to perform an out-of-plane displacement with respect to a plane defined by the electrode structure due to the kinetic energy while the first membrane portion remains at an originating side of the electrode structure.

Further embodiments of the present invention provide a method for manufacturing an electrostatic loudspeaker. The method comprises forming a membrane structure and forming an electrode structure. The membrane structure comprises a central membrane portion and a circumferential membrane portion. The central membrane portion is displaceable with respect to the circumferential membrane portion in a direction substantially orthogonal to an extension of the membrane structure. The electrode structure comprises a circumferential electrode portion and an opening. The circumferential electrode portion is substantially aligned to the circumferential membrane in a direction substantially orthogonal to an extension of the membrane structure and of the electrode structure. The opening is substantially aligned to the central membrane portion in the direction substantially orthogonal to the extension of the membrane structure and of the electrode structure so that the central membrane portion is configured to extend through the opening when being in an end position of a movement of the membrane structure while the circumferential membrane portion remains at one side of the electrode structure.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the present invention are described herein, making reference to the appended drawings.

FIG. **1**A shows a schematic cross section of an electrostatic loudspeaker according to an embodiment of teachings disclosed herein with a membrane structure being at a rest position;

FIG. **1**B shows a schematic cross section of the electrostatic loudspeaker from FIG. **1**A with the membrane structure being in an end position of a displacement;

FIG. **2**A shows a schematic, perspective cross section of an electrostatic speaker according to an embodiment of teachings disclosed herein with the membrane structure being at its rest position;

FIG. **2**B shows a schematic, perspective cross section of the electrostatic loudspeaker from FIG. **2**A with its membrane structure being in an end position of a displacement;

FIG. **3** illustrates a dependency of a required pull-in voltage on an effective electrode area;

FIG. **4** shows perspective view of a cross section of a simulated membrane structure;

FIGS. **5**A and **5**B show schematic cross sections through an electrostatic loudspeaker according to an embodiment of the teachings disclosed herein having an additional mass at a central membrane portion at a rest position and an end position, respectively;

FIG. **6** shows a schematic cross section of an electrostatic loudspeaker according to an embodiment of the teachings disclosed herein having a double back plate configuration;

FIG. **7** shows a schematic cross section of an electrostatic loudspeaker according to an embodiment of the teachings disclosed herein having membrane corrugations;

FIGS. **8**A and **8**B show a schematic cross section and a schematic top view, respectively, of an electrostatic loudspeaker according to an embodiment of the teachings disclosed herein having a hinge supported membrane structure;

FIGS. **9**A and **9**B show a schematic cross section and a schematic top view, respectively, of an electrostatic loudspeaker according to an embodiment of the teachings disclosed herein having a floating membrane structure;

FIGS. **10**A and **10**B show schematic cross sections of an electrostatic loudspeaker according to a further embodiment of the teachings disclosed herein at a rest position and an end position of the membrane structure, respectively;

FIG. **11** shows a schematic flow diagram of a method for operating an electrostatic loudspeaker according to teachings disclosed herein; and

FIG. **12** shows a schematic flow diagram of a method for manufacturing an electrostatic loudspeaker according to teachings disclosed herein.

Equal or equivalent elements or elements with equal or equivalent functionality are denoted in the following description by equal reference numerals or similar reference numerals. Furthermore, some functionally equal elements may also be provided with similar reference numbers wherein the two last digits are equal. Hence, descriptions provided for elements with the same reference numbers or with similar reference numbers are mutually exchangeable, unless noted otherwise.

DETAILED DESCRIPTION

In the following description, a plurality of details are set forth to provide a more thorough explanation of embodiments of the present invention. However, it will be apparent to one skilled in the art that embodiments of the present invention may be practiced without these specific details. In other instances, well known structures and devices are shown in schematic cross-sectional views or top-views rather than in detail in order to avoid obscuring embodiments of the present invention. In addition, features of the different embodiments described hereinafter may be combined with other features of other embodiments, unless specifically noted otherwise.

In order to satisfactorily fulfill its purpose, a loudspeaker typically has to provide large volume displacement to generate sufficient sound pressure level. Loudspeakers typically generate volume flow by displacement of a fluid, such as air. The displacement is obtained, in a large number of loudspeaker types, by a parallel movement relative to the sound propagation direction. This is true for many types of dynamic, piezoelectric, ferroelectric, or electrostatic loudspeakers in the macroscopic as well as in the microscopic implementation. Hence, large displacements are needed which is difficult on the microscopic level of implementation, especially. In particular, a large volume displacement out of a small area typically goes along with a need for a large out-of-plane displacement. Especially for micromechanically driven speakers this is in contrast to the microscopic nature of the fabricated devices, as vertical structure are typically only in the range of a few micrometers while a preferred displacement should be in a range from approximately 10 μm to approximately 100 μm. For example, the membrane of a MEMS transducer is typically manufactured using a sacrificial layer, for example silicon oxide (SiO_2). In use the amplitude of the membrane movement in some types of electrostatic loudspeakers is typically limited by approximately the thickness of the sacrificial layer because of structures formed on the sacrificial layers during the manufacturing process prior to (partly) removing the sacrificial layer, thus leaving the formed structures.

The teachings disclosed herein describe some options for generating a large out-of-plane displacement of a sound generating membrane that is fabricated by, for example, planar MEMS technologies with only small or typical error gap distances.

FIG. **1**A shows a schematic cross section of an electrostatic loudspeaker **100** according to an embodiment of the teachings disclosed herein. The electrostatic loudspeaker **100** comprises a substrate **110** that functions as a support structure or a part of a support structure. The substrate **110** may comprise a semiconductor material, such as silicon. The substrate **110** comprises a first main surface **118** and a second main surface **119** that is substantially parallel to the first main surface **118**. A cavity or trench **112** is formed in the substrate **110**. The cavity **112** extends from the first main surface **118** to the second main surface **119** so that the cavity **112** is in fact a through hole. In alternative configurations the cavity **112** could be a blind hole extending from the first main surface **118**. Furthermore, the cross section of the cavity **112** in a plane parallel to the first and second main surfaces **118**, **119** is not necessarily uniform but could, for example, taper or widen up from the first main surface **118** to the second main surface **119**.

A membrane structure **124** and an electrode structure **146** are arranged on the first main surface **118** of the substrate **110**. A spacer **132** is interposed between the first main surface **118** and the membrane structure **124**. The spacer **132** may provide an electrical isolation between the membrane structure **124** and the substrate **110**. In some embodiments of the electrostatic loudspeaker **100** the membrane structure **124** may be arranged directly on the first main surface **118** of the substrate **110**. In this case, an electrical isolation may be provided by isolating elements either within the membrane structure **124** or the substrate **110** or both.

The membrane structure **124** comprises a central membrane portion **125** and a circumferential membrane portion **126**. Note that the electrostatic loudspeaker **100** is illustrated having a rotational symmetry in FIG. **1**A so that the circumferential membrane portion **126** is substantially a ring and the central membrane portion **125** is substantially a circular disk. An outer part of the circumferential membrane portion **126** is attached to the spacer **132**. The central membrane portion **125** and the circumferential membrane portion **126** may be structurally identical or similar, i.e., the distinction between the central membrane portion **125** and the circumferential membrane portion **126** may be due to different functions/behaviors of the central membrane portion and the circumferential membrane portion. Moreover, the membrane structure **124** may or may not comprise special transition structures at the border between the circumferential membrane portion **126** and the central membrane portion **125**.

As an alternative to the rotational symmetry of the electrostatic loudspeaker **100** implied in FIG. **1**A, the electrostatic loudspeaker could have an elliptical shape, a rectangular shape, a square shape, a hexagonal shape, or an octagonal shape, to name a few.

The electrode structure comprises a circumferential electrode portion **146** and an opening **147**. The circumferential electrode portion **146** is substantially aligned to the circumferential membrane portion **126**. The opening **147** is substantially aligned to the central membrane portion **125** with respect to a direction parallel to an axis of movement. The axis of movement of the membrane structure **124** is perpendicular to a main surface of the membrane structure **124**. As can be seen in FIG. **1***b* the membrane structure **124** periodically moves towards the electrode structure during an operation of the electrostatic loudspeaker. The electrode structure **146** is arranged on a further spacer **136**. The spacer **136** is arranged on a first main surface of the membrane structure **124**. The spacer **136** may function as an electrical isolator between the membrane structure **124** and the electrode structure, in particular the circumferential electrode portion **146**. The spacers **132** and the **136** are typically the residuals of earlier existing sacrificial layers that were removed during a manufacturing process of the electrostatic loudspeaker **100**, especially in an extension of the cavity **112** along the axis of movement. The spacer **136** and the earlier sacrificial layer have a thickness s which also defines a spacing between the electrode structure and a rest position of the membrane structure **124**. Sacrificial layers typically have a thickness of a few micrometers only. Thicker sacrificial layers tend to be relatively costly during manufacturing.

The circumferential electrode portion **146** of the electrode structure comprises an edge **148** that delimits the opening **147**.

FIG. **1**B shows the electrostatic loudspeaker **100** during operation and in particular when the membrane structure **124** is in an end position of its movement. In this situation the circumferential membrane portion **126** partially contacts the circumferential electrode portion **146** at the edge **148** and/or the vicinity thereof. The central membrane portion **125** extends through the opening **147**. The movement or displacement of the membrane structure **124** is indicated in FIG. **1**B by a thick arrow. In the end position illustrated in FIG. **1**B the central membrane portion **125** is displaced by an amplitude A.

The movement of the membrane structure **124** is caused by creating an electrostatic force between the membrane structure **124** and the electrode structure. To this end, a voltage source **150** is electrically connected via a first connection **154** to the membrane structure **124** and via a second connection **156** to the circumferential electrode portion **146**. When an electrical voltage is applied between the membrane structure **124** and the circumferential electrode structure **146**, an attractive electrostatic force is created between these elements. As the circumferential electrode portion **146** is fixed to the spacer **136** and relatively rigid, the more flexible membrane structure **124** is deformed by the electrostatic force. A suspended part of the circumferential portion **126** accelerates and this acceleration is also transferred to the central membrane portion **125**, due to a mechanical coupling between the circumferential membrane portion and the central membrane portion. In this manner, the central membrane portion **125** builds up kinetic energy during a first phase of the movement of the membrane structure. The first phase of the movement continues approximately until the circumferential membrane portion **126** contacts the circumferential electrode portion **146**. During a second phase of the movement the central membrane portion **125** continues in the same direction as during the first phase which causes the central membrane portion to extend (at least partially) through the opening **147** of the electrode structure. In other words, the central membrane portion performs an out-of-plane displacement with respect to a plane defined by the electrode structure. With an increasing displacement from the rest position of the membrane structure, elastic forces increase within the membrane structure **124**. The elastic forces oppose the movement caused by the kinetic energy. Accordingly, the central membrane portion **125** decelerates and eventually begins a returning movement towards the rest position once it has reached the end position which is depicted in FIG. **1**B.

In FIG. **1**B the end position amplitude A is illustrated as being substantially greater than the spacing between the electrode structure and the rest position of the membrane structure **124**. In typical configurations of the electrostatic loudspeaker **100** the amplitude A of the central membrane portion **125** may be greater than the spacing s by at least 5% ($A \geq 1.05*s$), at least 10% ($A \geq 1.1*s$), at least 20% ($A \geq 1.2*s$), at least 50% ($A \geq 1.5*s$), at least 75% ($A \geq 1.75*s$), or at least 100% ($A \geq 2*s$).

The central membrane portion **125** may be configured to deflect when extending through the opening **147** as a result of the kinetic energy of the central membrane portion **125** due to the movement of the membrane structure **124**.

As it is possible that the membrane structure **124** contacts the circumferential electrode portion **146**, at least one of the membrane structure **124** and the circumferential electrode portion **146** may be electrically isolated to prevent an electrical short circuit. However, a mechanical contact between the membrane structure **124** and the circumferential electrode portion **146** is not absolutely necessary, and even in the end position of the membrane structure **124** a small gap or spacing may be maintained between the membrane structure **124** and the circumferential electrode portion **146**. This may be achieved by controlling the voltage V provided by the voltage source **150** to be smaller than a pull-in voltage V_pull-in. When the voltage V is greater than the pull-in voltage V_pull-in, a mechanical contact occurs between the membrane structure **124** and the circumferential electrode portion **146**, typically at or in the vicinity of the edge **148**.

According to the teachings disclosed herein the membrane structure **124** is actuated on the outer portion of the membrane (ring) **126**, for example by electrostatic pull-in. The inner portion **125** of the membrane structure **124** is accelerated by this actuation to stretch out of the actuation plane. The actuation plane is defined by a surface of the circumferential electrode portion **146** facing the membrane structure **124**. The driving kinetic energy is defined by the membrane velocity (fast pull-in displacement) and the membrane's mass as well as an equivalent mass of accelerated air around the membrane.

The electrostatic loudspeaker **100** shown in FIGS. **1**A and **1**B and also other electrostatic loudspeakers according to the teachings disclosed herein may be used for digital sound reconstruction, in particular when it is operated at or close to a resonance frequency of the membrane structure **124**.

In contrast to other designs of electrostatic loudspeakers the central membrane portion **125** can move freely not loosing energy against a limiting device such as a closed back plate functioning as a counter electrode. Nevertheless, the pull-in voltage V_pull-in on the ring portion **126** is still low enough to drive the electrostatic loudspeaker with reasonable voltages.

To summarize and according to at least one aspect of the teachings disclosed herein, a membrane is actuated in a small area only to drive the actuation of the full membrane to larger displacement in the free area utilizing its kinetic energy. One embodiment relates to a ring-actuated capacitive microspeaker.

FIGS. **2**A and **2**B show perspective views of cross sections of an electrostatic loudspeaker **200** according to another embodiment of the teachings disclosed herein, namely an implementation in a parallel double back plate construction. The electrostatic loudspeaker **200** differs from the electrostatic loudspeaker **100** illustrated in FIGS. **1**A and **1**B in that it comprises a further electrode structure. The further electrode structure is arranged between the substrate **110** and the membrane structure **124** and comprises a circumferential electrode portion **142** and an opening **143**. The opening **143** is delimited by an edge **144** of the further electrode structure. The spacer **132** is now interposed between the further electrode structure **142** and the membrane structure **124**. The further electrode structure **142** is arranged on a main surface of an etch stop layer **217** or another auxiliary layer covering the first main surface **118** of the substrate **110**. The etch stop layer **217** may be used to stop an etching step of a method for manufacturing the electrostatic loudspeaker **200**, in particular an etching step that is used to form the cavity **112** in the substrate **110**. Accordingly, the etch stop layer **217** comprises a different material than the substrate so that the cavity **112** may be selectively etched and the etch stop layer **217** is preserved until a subsequent selective etching step. The further electrode is connected to a voltage source via a further connection **152**. As can be seen in FIG. **2***b*, the central membrane portion **125** of the membrane structure **124** bulges out of the opening **147** in the electrode structure when the membrane structure **124** is in an upper end position of its movement. In an analog manner, the membrane structure **124** may be brought in a lower end position in which the central membrane portion **125** bulges out of the further opening **143** of the further electrode structure. In the lower end position the membrane structure **124** bends at the edge **144** of the circumferential electrode portion **142**.

The electrostatic loudspeaker **200** is, in principle, capable of doubling or even more than doubling an effect achieved by the electrostatic loudspeaker **100** shown in FIGS. **1**A and **1**B. This is particularly true if the electrostatic loudspeaker **200** is fabricated with an actuation ring above the upper surface of the membrane and an actuation ring below the lower surface of the membrane and when it is driven in a push-pull mode. The positional and directional terms “above”, “upper”, “below”, and “lower” refer to the depiction of the electrostatic loudspeaker **200** in FIGS. **2**A and **2**B, and by no means to be understood as limiting. This is also true for other figures and their respective descriptions.

When the membrane structure **124** is to be accelerated towards the further electrode structure **142**, the voltage source **150** is connected between the connection **154** and the connection **152** in order to apply the voltage V between the membrane structure **124** and the further electrode **142**.

FIG. **3** shows a result of a numerical simulation in the context of which the pull-in voltage V_pull-in has been determined in dependency on a ratio between the area of the circumferential electrode portion **146** and the total deflectable area of the membrane structure **124**. In a first simulation the back plate or circumferential electrode **346***a* is in fact a full disc having a diameter of 1 mm and an area of approximately $7.08\times10^{-7}\mathrm{m}^2$. With the full disc the pull-in voltage is approximately 11V.

In a second simulated case the circumferential electrode portion **346***b* has a width equal to half the radius r of the deflectable area of the membrane structure. This leaves an opening **347***b* having a radius r/2=0.0.25 mm that is also equal to half the radius r of the deflectable of the membrane structure. The ring-shaped circumferential electrode portion **346***b* has an area of approximately $5.31\times10^{-7}\ \mathrm{m}^2$. In this configuration a pull-in voltage V_pull-in of approximately 16V is required for causing a mechanical contact between the membrane structure and the electrode structure.

A third simulated case relates to a quarter radius ring in which the circumferential electrode portion **346***c* has a width equal to a quarter of the radius r of the deflectable area of the membrane portion. Accordingly, the opening **347***c* has a radius equal to 3/4r. The circumferential electrode portion **346***c* has an area of approximately $3.1\times10^{-7}\mathrm{m}^2$ and the required pull-in voltage is approximately V=33V.

These simulation results show that pull-in is still possible with only a partial back plate or circumferential electrode portion. For the purposes of simulation a membrane having a diameter of 1 mm and a thickness of 330 nm has been assumed. A tensile stress within the membrane was assumed to be 43 MPa and an air gap between the membrane structure and the electrode structure was assumed to be 2 μm.

FIG. **4** shows perspective view of a cross section of a simulated membrane structure. In particular, FIG. **4** shows a segment of a circular membrane structure **424** comprising a circumferential membrane portion **426** and a central membrane portion **425**. The abscissa of the graph in FIG. **4** represents a radius from a center of the circular membrane structure and the ordinate illustrates the deflection of the membrane structure **424**. A mechanical contact between the membrane structure **424** and an electrode structure (not shown) occurs approximately at the location indicated by reference numeral **421**. At this location, a limited pull-in occurs.

FIG. **4** illustrates one simulation result of several simulations using different input signals for driving the membrane structure **424**. The input signal was a step function with different amplitudes for the different simulation cases. During a first simulation the amplitude of the input signal was approximately the pull-in voltage of the membrane structure and the electrode structure. In this case the membrane movement at the edge of the ring is limited to a displacement of 1.6 μm.

The result of a second simulation is illustrated in FIG. **4**. The input signal was ramped up within 0.1 ms from 0V to 34V. A center deflection of more than 1.8 μm is achieved which translates to 0.2 μm additional displacement compared to the pull-in case.

In a third simulation, the result of which is not shown, an input signal is ramped up in 0.1 ms from 0V to 50V. A center deflection of 2.2 μm can be observed which is 0.6 μm additional displacement.

The resonance case was also simulated and it was shown that +/−5 μm displacement is possible with **100**kHz actuation having a peak-to-peak swing of 34V. Accordingly, the electrostatic loudspeaker according to the teachings disclosed herein may be used for digital sound reconstruction in which the electrostatic loudspeaker is operated using a carrier signal of, for example, 100 kHz. In this mode of operation high acceleration of the membrane structure may be generated and thus relatively large additional displacements are possible. Driving the electrostatic loudspeaker in self resonance may further increase the amplitude (for simulation purposes, air damping needs to be taken into account).

FIGS. **5**A and **5**B show schematic cross sections of an electrostatic loudspeaker **500** according to the teachings disclosed herein with the membrane structure **524** being at a rest position (FIG. **5**A) and in an end position (FIG. **5**B). The membrane structure **524** comprises an additional mass **527** on the central membrane portion **525**. The additional mass **527** increases the kinetic energy of the membrane structure **524** while the membrane structure **524** moves from the rest position towards the end position illustrated in FIG. **5**B. When the circumferential membrane portion **526** mechanically contacts or abuts at the circumferential electrode portions **146**, the increased kinetic energy of the central membrane portion **525** including the additional mass **527** causes an increase in the maximal displacement which in turn results in higher sound pressure levels. With the additional mass **527** the central membrane portion **525** has a higher mass-to-area ratio than the circumferential membrane portion **526**. The high mass-to-area ratio of the central membrane portion **525** may also be achieved with other measures, such as gradually increasing a thickness of the membrane structure **524** from the circumferential membrane portion **526** to the central membrane portion **525**.

FIG. **6** shows a schematic cross section of an electrostatic loudspeaker **600** according to a further embodiment of the teachings disclosed herein. The electrostatic loudspeaker **600** is similar to the electrostatic loudspeaker **200** from FIGS. **2**A and **2**B. The electrostatic loudspeaker **600** comprises a double back plate. The (upper) electrode structure with the circumferential electrode portion **146** and the opening **147** is a part of the double back plate structure. The (lower) electrode structure with the circumferential electrode portion **142** and the opening **143** is a part of the double back plate structure, too. As a difference to the electrostatic loudspeaker **200** shown in FIGS. **2**A and **2**B, the circumferential electrode portion **142** is arranged directly on the first main surface **118** of the substrate **110**, whereas in the electrostatic loudspeaker **200** these two elements were separated by the etch stop layer **217**.

To summarize, the electrostatic loudspeaker **600** shown in FIG. **6** comprises a further electrode structure **142**, **143** which is arranged at an opposite side of the membrane structure **124** than the (upper) electrode structure. The further electrode structure comprises a further opening **143** and a further circumferential electrode portion **142**. The central membrane portion **125** is configured to extend through the further opening **143** at least partially when being in a further end position of the movement of the membrane structure **124**.

FIG. **7** shows a schematic cross section of an electrostatic loudspeaker **700** according to a further embodiment of the teachings disclosed herein. With the exception of the membrane structure **724** the electrostatic loudspeaker **700** is similar to the electrostatic loudspeaker **600** shown in FIG. **6**. The membrane structure **724** comprises a circumferential membrane portion and a central membrane portion **725**. The membrane structure **724** further comprises corrugations **728** which are arranged between (at a transition of) the central membrane portion **725** and the circumferential membrane portion **726**. The corrugation **728** may be ring-shaped and provide a flexion structure between the central membrane portion **725** and the circumferential membrane portion **726**. Such a flexion structure could comprise several corrugations or other elements such as hinges. The corrugation **728** facilitates a bending of the membrane structure **724** at the transition from the circumferential membrane portion **726** to the central membrane portion **725**. An out-of-plane displacement of the central membrane portion **725** may thus be increased so that the central membrane portion **725** may extend still further through opening **147** of the circumferential membrane portion **146**.

FIGS. **8**A and **8**B show a schematic cross section and a schematic top view of an electrostatic loudspeaker **800** according to a further embodiment of the teachings disclosed herein. The electrostatic loudspeaker **800** comprises a membrane structure **824** that is hinge supported. The membrane structure **824** comprises hinges **823** which are schematically illustrated in the schematic cross section of FIG. **8**A and more clearly visible in the schematic top view of FIG. **8**B. In particular, four hinges **823** mechanically connect a deflectable or displaceable area of the membrane with the spacers **132** and **136**, which in turn are fixedly attached to the substrate **110** via the (lower) circumferential electrode portion **142**. As the hinges **823** are relatively narrow, the membrane structure **824** may easily bend in these regions. The hinges **823** are part of the circumferential membrane portion **826**. The central membrane portion **825** may extend through the opening **147** in the electrode structure when the membrane structure **824** is in (or near) the upper end position of the membrane structure movement. In an analog manner the central membrane portion **825** may extend through the opening **143** (at least partially) when the membrane structure **824** is at or near the (lower) end position of the membrane structure movement. The hinges **823** produce a weaker restoring force when the membrane structure **824** is displaced due to the electrostatic force exerted by the electrode structures **146**, **142** than in a configuration in which the membrane structure **824** is mechanically connected to the spacers **832**, **836** (more or less) at its entire circumference. Therefore, the membrane structure **824** may experience a stronger acceleration in the electrostatic loudspeaker **800** than in, for example, the electrostatic loudspeaker **600** shown in FIG. **6**. An increase in the acceleration of the membrane structure **824** causes an increase of the kinetic energy of the central membrane portion **825** at an instant of the membrane structure movement when the mechanical contact between the circumferential membrane portion **826** and the circumferential electrode portion **146** or **142** occurs. This increased kinetic energy causes an increased maximal displacement of the central membrane portion **825** in the end position of the membrane structure movement.

FIGS. **9**A and **9**B show a schematic cross section and a schematic top view, respectively, of an electrostatic loudspeaker **900** according to a further embodiment of the teachings disclosed herein. The electrostatic loudspeaker **900** comprises a floating membrane structure **924**. The floating membrane structure **924** comprises a circumferential membrane portion **926** and a central membrane portion **925**. The floating membrane **924** is not specifically mechanically connected to the surrounding structures, such as the spacer **932** or the circumferential electrode portions **142**, **146**. Instead, the floating membrane structure **924** is arranged within a gap **930** delimited by the (lower) circumferential electrode portion **142**, the (upper) circumferential portion **146**, and the spacer **932**. The floating membrane structure **924** may move more or less freely within the gap **930**, but it cannot leave the gap **930**, because it is larger than the openings **147** and **143**. During an operation of the electrostatic loudspeaker **900** the circumferential portion **926** may get in mechanical contact with or abut at the circumferential electrode portions **142**, **146**. While the movement of the circumferential membrane portion **926** is stopped by this mechanical contact, the central membrane portion **925** may continue its movement until it reaches one of the two end positions. Accordingly, the central membrane portion **925** may extend at least partially through the openings **143** and **147** during some phases of the movement and/or perform an out-of-plane displacement.

For the generation of a significant electrostatic force the floating membrane structure **924** needs to be electrically charged. This may be achieved by implanting electrical charges into the floating membrane structure during a manufacture of the electrostatic loudspeaker **900**. These implanted electrical charges are typically well isolated in order to prevent a withdrawal of the electrical charges and to achieve a good long time stability. Another option for electrically charging the membrane structure **924** is shown in FIG. 9B, in which the membrane structure **924** comprises an electrical connection **954**. The electrical **954** is highly flexible so that the membrane structure **924** can still be regarded as a floating membrane structure.

FIGS. **10**A and **10**B show schematic cross sections of an electrostatic loudspeaker **1000** at a rest position and an end position of its membrane structure **1024**. The membrane structure **1024** is configured for a displacement along an axis of movement indicated by the arrow in FIG. **10**B. The electrostatic loudspeaker **1000** further comprises an electrode structure **1046** configured to electrostatically interact with the membrane structure **1024** for causing the displacement. A projection of the electrode structure **1046** on the membrane structure **1024** along the axis of movement defines a first portion **1026** of the membrane structure **1024**. The membrane structure **1024** further comprises a second portion **1025**.

The electrostatic loudspeaker **1000** has an opening **1047** which is delimited by the electrode structure **1046** at one side. At another side, the opening **1047** is delimited by a wall **114** which is arranged on the first main surface **118** of the substrate **110**. The membrane structure **1024** is configured so that the second portion **1025** deflects, due to a kinetic energy caused by the movement, at an edge **1048** of the electrode structure during a phase of the movement of the membrane structure **1024**. Accordingly, the second portion **1025** is configured to perform an out-of-plane displacement with respect to a plane **1040** defined by the electrode structure **1046**.

The wall **114** may comprise a curved surface **115** facing the electrode structure **1046** so that an excessive leakage of air (or fluid) moved by the membrane structure **1024** around an end of the second portion **1025** is prevented.

The projection of the electrode structure **1046** on the membrane structure **1024** to define the first portion of the membrane structure is typically done in a direction perpendicular to the plane **1040**. Accordingly, the projection is performed along an axis of movement during an initial phase of the membrane structure movement, i.e. when the membrane structure **1024** is at or close to the rest position. In the alternative, the projection could be defined by observing at which location of the membrane structure **1024** a contact with the edge **1048** is first established during the movement of the membrane structure **1024**.

The first portion **1026** corresponds to the circumferential membrane portion of the electrostatic loudspeakers **100**, **200**, **500**, **600**, **700**, **800**, **900** described above. The second membrane portion **1025** corresponds to the central membrane portion of the electrostatic loudspeakers **100**, **200**, **500**, **600**, **700**, **800**, **900** described above. The edge **1048** of the electrode structure **1046** delimits the opening **1047** within the electrode structure **1046** so that the second membrane portion **1025** is configured to extend, when being in an end position of the movement, through the opening **1047** while the first membrane portion **1026** remains at an originating site of the electrode structure **1046**. The originating side of the electrode structure **1046** is the side at which the membrane structure **1024** is located.

The electrostatic loudspeaker according to the teachings disclosed herein may be a micro electrical mechanical system (MEMS). Furthermore, the micro electrical mechanical system may be based on planar micro electrical mechanical system technology. The electrostatic loudspeaker may be a digital loudspeaker.

The membrane structure may comprise a corrugation. The membrane structure may be configured to be driven in a resonance mode or a self-resonance mode. In addition or in the alternative, the circumferential membrane portion may be configured to temporarily abut at the circumferential electrode portion during the movement of the membrane structure.

FIG. **11** shows a schematic flow diagram of a method for operating an electrostatic loudspeaker. The method comprises a step **1102** of applying an electrical voltage between a first electrode at a membrane structure and a second electrode at an electrode structure, wherein a projection of the electrode structure on the membrane structure along an axis of a movement of the membrane structure defines a first membrane portion of the membrane structure and wherein the membrane structure further comprises a second membrane portion. This means that the electrode structure is in the way of the first membrane portion when the membrane structure performs the movement. However, the movement of the second membrane portion is not blocked by the electrode structure.

During a method step **1104** the membrane structure is accelerated towards the electrode structure due to an electrostatic action between the first electrode and the second electrode. The acceleration of the membrane structure increases a kinetic energy of the membrane structure. The electrostatic action occurs mainly between the first membrane portion and the electrode structure. An electrostatic action between the second membrane portion and the electrode structure is typically weaker. Nevertheless, configurations of the electrostatic loudspeaker according to the teachings disclosed herein are imaginable in which the electrostatic action between the second membrane portion and the electrode structure is approximately as strong as the electrostatic action between the first membrane portion and the electrode structure, or even stronger. In any event, the second membrane portion is also accelerated as it is mechanically coupled to the first membrane portion.

At a step **1106** the second membrane portion is caused to perform an out-of-plane displacement with respect to a plane defined by the electrode structure. The out-of-plane displacement is due to the kinetic energy built up during the acceleration of step **1104**. Meanwhile, the first membrane portion remains at an originating site of the electrode structure, as its movement is blocked by the electrode structure.

In the following, a number of possible configurations, implementations, further specifications and features of the method for operating an electrostatic loudspeaker are discussed. The second membrane portion may deflect while going beyond the plane defined by the electrode structure, i.e. while performing the out-of-plane displacement with respect to the plane defined by the electrode structure.

The first membrane portion may be a circumferential membrane portion and the second membrane portion may be a central membrane portion of the membrane structure. The edge of the electrode structure may delimit an opening within the electrode so that the second membrane portion extends, when being in an end position of the movement, through the opening while the first membrane portion remains at an originating side of the electrode structure.

The electrostatic loudspeaker may be a micro electrical mechanical system (MEMS).

The method for operating the electrostatic loudspeaker may further comprise one or more of the following steps. An electrical voltage may be applied between the first electrode and a third electrode at a further electrode structure arranged at an opposite side of the membrane structure than the (above mentioned) electrode structure. The membrane structure may be accelerated towards the further electrode structure due to an electrostatic action between the first electrode and the third electrode. As a consequence, the kinetic energy of the membrane structure is increased. The second membrane portion may be caused to go beyond a further plane defined by the further electrode structure due to the kinetic energy while the first membrane portion remains at a side of a rest position of a further electrode structure (originating side). In other words, the second membrane portion may be caused to perform a further out-of-plane displacement with respect to the further plane defined by the further electrode structure.

FIG. **12** shows a schematic flow diagram of a method for manufacturing an electrostatic loudspeaker. The method for manufacturing an electrostatic loudspeaker comprises a step **1202** of forming a membrane structure and a step **1204** of forming an electrode structure. The membrane structure comprises a central membrane portion and a circumferential membrane portion. The central membrane portion is displaceable with respect to the circumferential membrane portion in a direction substantially orthogonal to an extension of the membrane structure. When the method for manufacturing an electrostatic loudspeaker is directed at the electrostatic loudspeaker **1000** illustrated in FIGS. **10**A and **10**B, the membrane structure comprises a first membrane portion and a second membrane portion which are defined by a projection of the electrode structure on the membrane structure along a direction of a movement of the membrane structure during operation of the electrostatic loudspeaker **1000**. Indeed, these definitions of the first and second membrane portions are also applicable to most of the other embodiments illustrated and discussed herein. The central membrane portion (second membrane portion) is displaceable with respect to the circumferential membrane portion (first membrane portion) in a direction substantially orthogonal to an extension of the membrane structure.

The electrode structure comprises a circumferential electrode portion and an opening. The circumferential electrode portion is substantially aligned to the circumferential membrane portion and the opening is substantially aligned to the central membrane portion in a direction substantially orthogonal to an extension of the membrane structure and of the electrode structure. Accordingly, the central membrane portion is configured to extend through the opening when being in an end position of a movement of the membrane structure while the circumferential membrane portion remains at one side of the electrode structure, i.e. the originating side.

In further embodiments of the method for manufacturing an electrostatic loudspeaker the central membrane portion may be formed to be deflectable with respect to the circumferential membrane portion in the direction substantially orthogonal to the extension of the membrane structure. The circumferential membrane portion may be formed as a substantially ring-shaped portion. The central membrane portion may be formed to have a higher mass-to-area ratio than the circumferential membrane portion.

The method for manufacturing an electrostatic loudspeaker may employ micro electrical mechanical system fabrication technology or planar micro electrical mechanical system fabrication technology.

Although some aspects have been described in the context of an apparatus, it is clear that these aspects also represent a description of the corresponding method, where a block or device corresponds to a method step or a feature of a method step. Analogously, aspects described in the context of a method step also represent a description of a corresponding block or item or feature of a corresponding apparatus. Some or all of the method steps may be executed by (or using) a hardware apparatus, like for example, a microprocessor, a programmable computer or an electronic circuit. In some embodiments, some one or more of the most important method steps may be executed by such an apparatus.

The above described embodiments are merely illustrative for the principles of the present invention. It is understood that modifications and variations of the arrangements and the details described herein will be apparent to others skilled in the art. It is the intent, therefore, to be limited only by the scope of the impending patent claims and not by the specific details presented by way of description and explanation of the embodiments herein.

The invention claimed is:

1. An electrostatic loudspeaker comprising:

a membrane structure comprising a central membrane portion and a circumferential membrane portion;

an electrode structure configured to electrostatically interact with the membrane structure for causing a movement of the membrane structure along an axis of movement, the electrode structure comprising a circumferential electrode portion and an opening, the circumferential electrode portion being substantially aligned to the circumferential membrane portion and the opening being substantially aligned to the central membrane portion with respect to a direction parallel to the axis of movement; and

a gap between the membrane structure and the electrode structure,

wherein, in an end position of the movement of the membrane structure, the central membrane portion is configured to extend at least partially through the opening, and

wherein an amplitude of the central membrane portion is greater than a thickness of the gap by at least 5%.

2. The electrostatic loudspeaker according to claim **1**, wherein the central membrane portion is configured to deflect when extending through the opening as a result of a kinetic energy of the central membrane portion due to the movement of the membrane structure.

3. The electrostatic loudspeaker according to claim **1**, wherein the circumferential electrode portion is substantially ring-shaped.

4. The electrostatic loudspeaker according to claim **1**, wherein the central membrane portion has a higher mass-to-area ratio than the circumferential membrane portion.

5. The electrostatic loudspeaker according to claim **1**, wherein the membrane structure comprises a flexion structure between the central membrane portion and the circumferential membrane portion.

6. The electrostatic loudspeaker according to claim **1**, wherein the electrostatic loudspeaker is a micro electrical mechanical system.

7. The electrostatic loudspeaker according to claim **6**, wherein the micro electrical mechanical system is based on planar micro electrical mechanical system technology.

8. The electrostatic loudspeaker according to claim **1**, further comprising a further electrode structure arranged at an opposite side of the membrane structure than the electrode structure and comprising a further opening and a further circumferential electrode portion,

wherein the central membrane portion is further configured to extend through the further opening at least partially when being in a further end position of the movement of the membrane structure.

9. The electrostatic loudspeaker according to claim **1**, wherein the electrostatic loudspeaker is a digital loudspeaker.

10. The electrostatic loudspeaker according to claim **1**, wherein the membrane structure comprises a corrugation.

11. The electrostatic loudspeaker according to claim **1**, wherein the membrane structure is hinge supported at a support structure.

12. The electrostatic loudspeaker according to claim **1**, wherein the membrane structure comprises a floating membrane.

13. The electrostatic loudspeaker according to claim **1**, wherein the membrane structure is configured to be driven in a resonance mode.

14. The electrostatic loudspeaker according to claim **1**, wherein the circumferential membrane portion is configured to temporarily abut at the circumferential electrode portion during the movement of the membrane structure.

15. An electrostatic loudspeaker comprising:

a membrane structure configured for displacement along an axis of movement;

an electrode structure configured to electrostatically interact with the membrane structure for causing movement of the membrane structure, wherein the electrode structure comprises an edge so that a projection of the electrode structure on the membrane structure along the axis of the movement defines a first membrane portion of the membrane structure and wherein the membrane structure further comprises a second membrane portion; and

a gap between the membrane structure and the electrode structure,

wherein the membrane structure is configured so that the second membrane portion deflects, due to a kinetic energy caused by the movement of the membrane structure so that the second membrane portion extends at least partially beyond a plane defined by a surface of the electrode structure facing away from the membrane structure.

16. The electrostatic loudspeaker according to claim **15**,

wherein the first membrane portion is a circumferential membrane portion and the second membrane portion is a central membrane portion, and

wherein the edge of the electrode structure delimits an opening within the electrode structure so that the second membrane portion is configured to extend, when being in an end position of the movement, through the opening while the first membrane portion remains at an originating side of the electrode structure.

17. A method for operating an electrostatic loudspeaker, the method comprising:

applying an electrical voltage between a first electrode at a membrane structure and a second electrode at an electrode structure wherein a projection of the electrode structure on the membrane structure along an axis of a movement of the membrane structure defines a first membrane portion of the membrane structure and wherein the membrane structure further comprises a second membrane portion;

accelerating the membrane structure along the axis of the movement towards the electrode structure due to an electrostatic action between the first electrode and the second electrode such that the membrane structure extends across a gap between the membrane structure and the electrode structure, thereby increasing a kinetic energy of the membrane structure; and

causing the second membrane portion of the membrane structure to perform an out-of-plane displacement so that the second membrane portion extends at least partially beyond a plane defined by a surface of the electrode structure facing away from the membrane structure due to the kinetic energy while the first membrane portion remains at an originating side of the electrode structure.

18. The method according to claim **17**, wherein the second membrane portion deflects while performing the out-of-plane displacement with respect to the plane defined by the electrode structure.

19. The method according to claim **17**, wherein the first membrane portion is a circumferential membrane portion and the second membrane portion is a central membrane portion, and

wherein an edge of the electrode structure delimits an opening within the electrode structure so that the second membrane portion extends, when being in an end position of the movement, through the opening while the first membrane portion remains at an originating side of the electrode structure.

20. The method according to claim **17**, wherein the electrostatic loudspeaker is a micro electrical mechanical system.

21. The method according to claim **17**, further comprising:

applying an electric voltage between the first electrode and a third electrode at a further electrode structure arranged at an opposite side of the membrane structure than the electrode structure;

accelerating the membrane structure towards the further electrode structure due to an electrostatic action between the first electrode and the third electrode, thereby increasing the kinetic energy of the membrane structure; and

causing the second membrane portion to go beyond a further plane defined by the further electrode structure due to the kinetic energy while the first membrane portion remains at a side of a rest position of the further electrode structure.

22. The method according to claim **17**, further comprising deflecting the second membrane portion with respect to the first membrane portion in a direction substantially orthogonal to an extension of the membrane structure.

23. The method according to claim **17**, wherein the electrode structure is formed as a substantially ring-shaped portion.

24. The method according to claim **17**, wherein the second membrane portion is formed to have a higher mass-to-area ratio than the first membrane portion.

25. An electrostatic loudspeaker comprising:

a membrane structure comprising a central membrane portion and a circumferential membrane portion;

an electrode structure configured to electrostatically interact with the membrane structure by causing a movement of the membrane structure along an axis of movement, the electrode structure comprising a circumferential electrode portion that defines an opening; and a gap between the membrane structure and the electrode structure,

wherein the central membrane portion is configured to extend at least partially through the opening when in an end position of the movement of the membrane structure, and to perform an out-of-plane displacement, in which the central membrane portion extends at least partially beyond a plane defined by a surface of the electrode structure facing away from the membrane structure.

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